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Marketing Research Report No. 455

U. S. DEPT. OF AGRICULTURE
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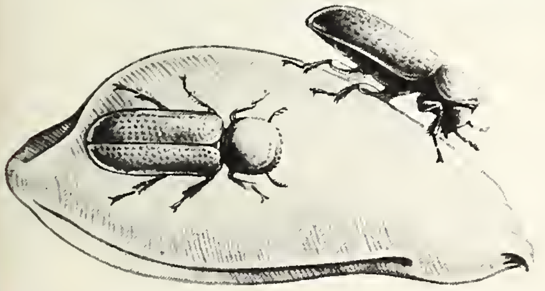
CURRENT SERIAL RECORDS

Effects of High-Frequency Electric Fields on Certain Species of Stored-Grain Insects



Market Quality Research Division
Agricultural Marketing Service
U.S. DEPARTMENT OF AGRICULTURE

PREFACE

This report, one of a group presenting the results of tests with physical and mechanical means applied to stored grain for the control of insect infestation, gives the results of a study on the effects of high-frequency electric fields on certain stored-grain insects. "Radio-Frequency Electric Fields for Stored Grain Insect Control," by S. O. Nelson and W. K. Whitney (Amer. Soc. Agr. Engin. Trans. 3(2) 1960) is a companion report dealing with the engineering aspects of the studies reported here.

These report a part of a broad program of research to reduce the cost of marketing farm products, including the cost of preventing or controlling insect infestation in stored grain.

The studies reported herein were initiated by N. M. Dennis, then of the Stored-Grain Insects Laboratory, Manhattan, Kans., and L. H. Soderholm, of the then Bureau of Plant Industry, Soils, and Agricultural Engineering, Lincoln, Nebr., and the earlier work was conducted by them. The work reported herein is a continuation and expansion of the studies from where they left the project.

The University of Nebraska supplied the laboratory space and electric power for the operation of the high-frequency apparatus.

CONTENTS

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Summary ii

Background and purpose of the work
- General principles of high-frequency treatments

Materials and apparatus
- Test insects
- Culture and exposure media
- Treatment apparatus

Procedure
- Preparation of samples
- Treatment procedure
- List of experiments

Results of the treatments
- Mortality of the test insects
  - Results with rice weevil adults 4
  - Results with immature stages of the rice weevil 4
  - Results with confused flour beetle adults 4
  - Results with confused flour beetle larvae 4
  - Results with red flour beetle adults 4
  - Results with granary weevil adults 4
  - Results with lesser grain borer adults 4
  - Results with immature stages of the lesser grain borer 4
  - Results with dermestid larvae 4

Reproduction studies 4

Discussion 4
- Injuries and delayed effects on exposed insects 4
- Comparison of the effects of treatment on adults and immature stages 4
- Comparison of wheat and wheat shorts as treatment media 4
- Differential heating of the insects and the treatment media 4

Costs of treatment 5

Findings 5

March 1961

SUMMARY

Certain species of insects in stored grain can be killed by a few seconds' exposure to high-frequency electric fields.

In studies conducted at Manhattan, Kans., 1956-57, insects in stored wheat and wheat shorts were exposed to high-frequency electrical treatments of different frequencies and field intensities to determine their effect on mortality and reproduction of the insects.

It was found that there are differences in the resistance of different species and between stages of a species of insect.

Treatment at a field intensity of 3.6 kilovolts per inch, root mean square (kv./in., r.m.s.) in grain was more efficient in killing adult stored-grain insects than treatment at lower field intensities of 2.4 or 1.2 kv./in.

No distinguishable difference was found in the susceptibility of the different immature stages to field intensities of 4.8 kv./in. or less.

The maximum field intensity which can be used is limited by arcing in the grain which burns the kernels.

Differential heating rates for the insects and the grain, when treated together, were found to agree closely with the theoretical prediction.

Higher level treatments were required to kill adult insects in wheat shorts than in wheat.

No difference was observed in the effectiveness of high-frequency treatment in wheat with 11.4 and 12.8 percent of moisture.

The order of increasing resistance of insects treated in wheat at about 39 megacycles frequency and 3.6 kv./in., as shown in this study, was: (1) rice weevil adults, (2) granary weevil adults, (3) confused flour beetle adults, (4) lesser grain borer adults, (5) dermestid larvae, (6) immature stages of the rice weevil, and (7) immature stages of lesser grain borer.

Insects not killed by the various exposures were injured when exposed to high field intensities. The injuries consisted of legs or antennae completely broken off, or the tibiae and tarsi missing. The injured insects often moved about on the stumps of the femora or tibiae. Most of the injured specimens died within a week after exposure.

Some reproduction occurred in adult rice weevils and confused flour beetles that survived exposure to the high-frequency fields.

The cost of treatment was estimated to range from 2.8 to 3.7 cents per bushel of wheat. This estimate included depreciation and maintenance of equipment, interest on investment, power cost, and labor for operation and maintenance.

EFFECTS OF HIGH-FREQUENCY ELECTRIC FIELDS ON CERTAIN SPECIES OF STORED-GRAIN INSECTS

by W. K. Whitney, S. O. Nelson, and H. H. Walkden[1]

BACKGROUND AND PURPOSE OF THE WORK

The use of high-frequency radio waves for killing insects is not new, but information on their effects on stored-grain insects is meager. To explore the possibilities in this field, cooperative studies of the effects of high-frequency electric fields on stored-product insects were conducted by the Stored-Product Insects Branch, Manhattan, Kans., and the Farm Electrification Research Branch, Agricultural Engineering Research Division, Agricultural Research Service, Lincoln, Nebr., during the period from September 1956 to June 1957. In these investigations different species and stages of stored-grain insects were exposed in a medium of wheat or wheat shorts to high-frequency electrical treatments of different frequencies and field intensities. Studies of mortality, injury, and insect reproduction after treatment were conducted to establish relationships between treatment variables and effects on the insects. Experimental results have also been examined for revelation of fundamental ideas concerning effects of high-frequency fields on the insects.

The reader is referred to the companion report cited inside the front cover.

General Principles of High-Frequency Treatment

When relatively poor conductors of electricity are placed in an alternating electric field with a frequency of a few million cycles per second (megacycles, abbreviated mc.), a heating effect is produced. This effect, known as dielectric heating, can be very rapid, an exposure of a few seconds being sufficient to elevate the temperatures of material being treated by 50 to 100 degrees F. Because the heat developed as energy is absorbed from the field, all parts of the material are heated simultaneously. Further, the rate of heating depends upon the electrical characteristics of the material. In mixtures of different substances, therefore, there is a possibility of advantageous selective heating. Both insects and grain fall into this class of relatively poor conductors of electricity, and are rapidly heated in a high-frequency field. The insects by themselves possess electrical characteristics that make them heat faster than grain. When mixed with the grain, other factors make it difficult to predict the selective heating behavior. Selective heating, however, seems to offer the most satisfactory explanation of the experimental results obtained. Most authorities believe that the lethal agent is heat, but few will absolutely exclude the possibility of other "special effects" which might be produced by the electrical treatment.

As the heating effect is the most obvious result of high-frequency treatment, some explanation of factors influencing the rate of heating should be offered here. The rate of heating, $\frac{d\theta}{dt}$, is given by the following mathematical equation:

$$\frac{d\theta}{dt} = \frac{K E^2 F \varepsilon''}{\rho c} \qquad \text{(Equation 1)}$$

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[1] Mr. Whitney and Mr. Walkden were formerly members of the staff of the Stored-Grain Insects Laboratory, Manhattan, Kans., a station of the Stored-Product Insects Branch, Market Quality Research Division, Agricultural Marketing Service, U. S. Department of Agriculture. Mr. Whitney has resigned, Mr. Walkden has retired. Mr. Nelson is agricultural engineer, Farm Electrification Research Branch, Agricultural Engineering Research Division, Agricultural Research Service.

where K is a constant of proportionality depending upon the units employed, F is the frequency of the applied field, E is the field intensity or voltage gradient in the material, ε'' is the dielectric loss factor of the material, ρ is the density, and c is the specific heat of the material.

MATERIALS AND APPARATUS

Test Insects

The following six species and different stages of insects were reared at the Manhattan laboratory and used in the tests:

1. The rice weevil (*Sitophilus oryza* (L.)), at these stages: adults (2 weeks after emerging from wheat); eggs ($\frac{1}{2}$ to 4 days old); eggs and young larvae (5 to 12 days old); larvae (12 to 19 days old); older larvae and pupae (19 to 26 days old); and pupae, a few older larvae, and pre-emergence adults (26 to 33 days old).

2. The granary weevil (*Sitophilus granarius* (L.)), as 2-week-old adults.

3. The confused flour beetle (*Tribolium confusum* Duv.), as last instar larvae and as 2-week-old adults.

4. The red flour beetle (*Tribolium castaneum* (Hbst.)), as 2-week-old adults.

5. The lesser grain borer (*Rhyzopertha dominica* (F.)), as mixed ages of adults and four separate groups of immatures of ages 1 to 5 days, 5 days to 2 weeks, 2 to 3 weeks, and 3 to $4\frac{1}{2}$ weeks. These groups of immatures were not as distinct as desired because some of the adult parents that bored into wheat kernels could not be removed by the conventional method of sifting. A few individuals in each age group were either older or younger than stated above; however, most of the insects were within the stated age range.

6. The dermestid *Trogoderma parabile* Beal as full-grown larvae about 1 month of age.

Culture and Exposure Media

The weevils and grain borers were reared in Hard Red Winter Wheat. Flour beetles were reared in wheat shorts fortified with 5 percent powdered brewers' yeast.[2] The moisture content of the culture media was adjusted to 12.5 percent before infestation. The culture room was kept at 80° F. and 65 percent relative humidity. Insects were separated from the culture media by sifting, and picked up with aspirators as they were counted.

The dermestid larvae were reared in a food medium consisting of the following ingredients:

Fine corn meal	4 parts
Wheat shorts	4 "
Pelleted or flaked dog food	2 "
Dried brewers' yeast	1 part
Honey	1 "
Glycerine	1 "
Wheat germ	$\frac{1}{2}$ "
Oatmeal	1 "

This mixture was diluted with an equal amount of wheat of 12-13 percent moisture content to make it less compact.

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[2] Shorts are composed of small particles of bran, germ, and flour.

Hard Red Winter Wheat (mostly Pawnee) was used in all tests except three tests with flour beetles in which wheat shorts were used. The flour beetles in one test were removed from the wheat and placed with wheat shorts at the time of the first mortality count. The weevils and borers were left with whole wheat throughout the entire test period. Dockage was removed from the wheat by screening with a No. 10 sieve and by aspiration with a Bates laboratory aspirator. The wheat shorts were sifted with a 20-mesh screen to remove the larger particles of bran.

Moisture content of the wheat and shorts was measured with a Steinlite Moisture Tester[3] and then adjusted to the desired percentages by drying in a forced-air oven at 90° F. or by addition of distilled water. The moisture content was also determined at Lincoln, Nebr., by an air-oven method[4] at the time of the high-frequency (HF) treatment. This oven method is the basis of the moisture contents recorded in this report. Tests RW_a-1 and RW_a-2 were designed to compare identical treatments of adult rice weevils in association with wheat of approximately 13 and 11 percent moisture. A moisture content of about 13 percent was intended for all of the other experiments. This is the moisture content of wheat at equilibrium with the conditions in the culture room (temperature 80° F., relative humidity 65 percent).[5]

Treatment Apparatus

Two HF power oscillators were used to treat the samples. One, operating on a fixed frequency of approximately 39 megacycles (mc.) per second, is a slightly modified General Electric Model 4HD3B2 Electronic Dielectric Heater. This unit, with a sample box resting on the lower electrode, is shown in figure 1. The adjustable grounded electrode is mounted in the top cover, which is hinged to the frame and brings the grounded electrode down and parallel to the stationary electrode when the cover is closed. These electrodes and the sample or load constitute the capacity of the plate tank circuit. Frequency of operation is therefore somewhat dependent upon the load. The unit employs a grounded-plate Hartley oscillator circuit and has an output rating of 3 kw. A Powerstat, Type 1256 variable transformer, was connected in the primary circuit of the plate transformer in the high-voltage power supply to provide for complete adjustment of the plate voltage applied to the oscillator. It can therefore be used to adjust the HF voltage at the treatment electrodes to the desired value. Other modifications and additions have been made in the timer control circuits to provide for shorter intervals and control by an external electronic timer.

The other HF oscillator (dielectric heater) was constructed for work at lower frequencies. It operates in the frequency range from 1.5 to 11 mc. and has a maximum power output of about 1 kw. It employs a tuned-plate oscillator with inductive coupling to the grid circuit. It is pictured in figure 2 where the separate power supply is partly visible below the recording potentiometer. Provisions were made for control of the treatment interval with external timers.

To control time intervals for the dielectric heaters, Cramer Type TE electric timers with maximum ranges of 15 sec. and 120 sec., an Eagle 30-second Cycl-Flex Reset Timer and Ferrara Model T1 and T2 Electronic Timers were used. When electronic timers were employed, their calibration was checked or the interval simultaneously measured with a Standard Electric Model S-1 Precision Timer.

The frequencies at which the HF equipment operated were measured with a Millen No. 90651 Grid-Dip Meter.

The HF electrode voltage was measured with a Hewlett-Packard, Model 410B High-Frequency Vacuum-Tube Voltmeter (VTVM) equipped with a 100:1 Hewlett-Packard Model

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[3] The use of trade names in this report is for identification purposes only and does not constitute endorsement of the products by the U. S. Department of Agriculture.

[4] Official Methods of Analysis of the Association of Official Agricultural Chemists (Ed. 7), Assoc. Official Agr. Chemists, Sect. 22.8, 1950.

[5] Coleman, D. A., and Fellows, H. C. Hygroscopic Moisture in Cereal Grains. Cereal Chem: 2:275-287, 1925.

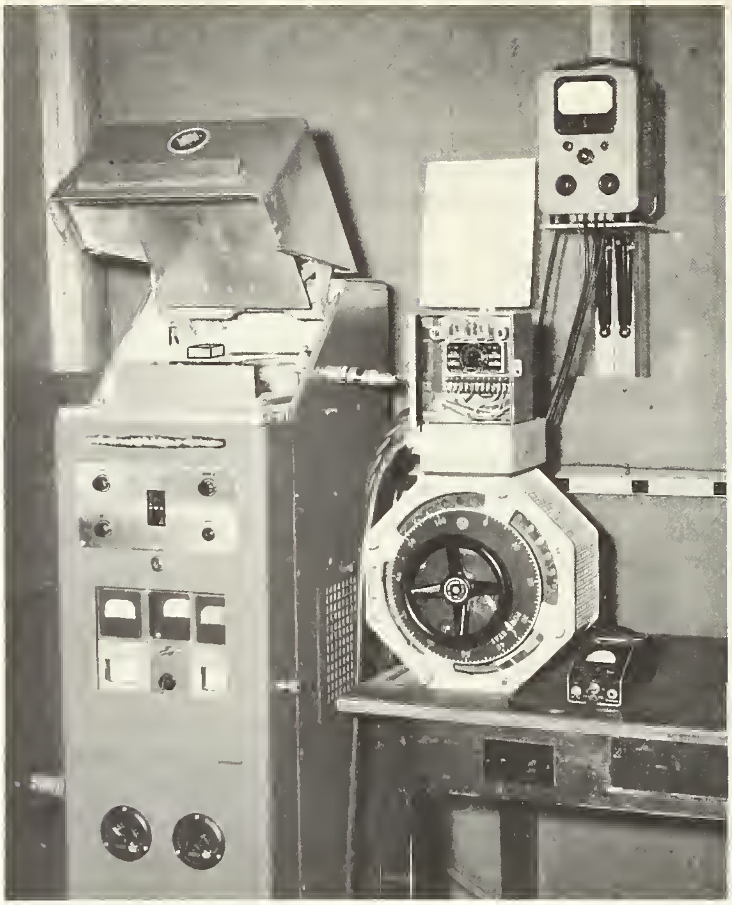

Figure 1.--Three-kw. dielectric heater used for 39-mc. treatments and associated equipment; variable transformer, vacuum tube voltmeter (VTVM), electronic timer and grid-dip meter.

Figure 2.--One-kw. power oscillator used for 10- and 11-mc. treatments.

453A capacitive voltage divider probe and additional 10:1 capacitive dividers which were built into the treatment chambers of the dielectric heaters. These additional dividers were necessary because of the 2,000 v., r.m.s. maximum voltage rating of the 453A probe. They were calibrated to provide a 10:1 voltage division at values below the maximum voltage rating of the probe. Treatment electrodes were adjusted to compensate for the capacity added by the 453A probe when connected directly to the electrode. The calibration of the VTVM was corrected to within 0.5 percent accuracy by comparison with laboratory meters at 60 c.p.s. The maximum probable error in measurement at 40 mc. due to frequency response of the instrument is about 5 percent, according to the manufacturer. Taking calibration of the capacitive voltage dividers into consideration, HF electrode voltages should be accurate to within less than 10 percent. The VTVM uses a peak measuring circuit with r.m.s. calibration for a sinusoidal input. Voltage and field strength values herein reported are therefore r.m.s. values.

Calculation of field intensity was simplified by treating all samples with the electrodes in contact with the top and bottom of the boxes, and with the boxes completely filled with wheat or wheat shorts. The average field intensity for the sample was calculated as follows:

$$E = \frac{V}{d_1 + d_2 \frac{\varepsilon_1}{\varepsilon_2}} \qquad \text{(Equation 2)}$$

where V is the HF electrode voltage and d_1 and d_2, and ε_1 and ε_2 are the thicknesses of the materials between the electrodes and their permittivities for the grain and polystyrene, respectively. The thickness for the grain, d_1, was given by the assembled height of the box less d_2, the combined thickness of the lid and bottom of the box. The permittivity of polystyrene, ε_2, is approximately 2.56. The permittivity of the wheat and wheat shorts used in each experiment was obtained by measurement according to the method previously reported.[6]

At the same time that electrical measurements were taken, moisture content determinations were made on samples from the same source in accordance with an approved oven method.

Temperatures of the media and the test insects were measured with a Leeds and Northrup Type G, Model S, strip chart, 10-point recording thermocouple potentiometer. A 10-pole, 10-position switch was constructed for use with copper-constantan thermocouples which permits the rapid selection of any desired combination of thermocouple-to-recorder point connections. The recorder, switch, and thermocouple mount are pictured in figure 3. The thermocouples were made from No. 30 B & S gage duplex copper-constantan wire with glass-braid insulation. They were held in such a way by the thermocouple mount that the thermocouples were easily inserted through the small hole in the side of the sample box as the box was placed on the mount (fig. 4.). Location of the thermocouple for the temperature measurement was as near the center of the box as possible. It was generally possible to obtain the temperature record on each sample within 5 to 10 seconds after treatment. While the cooling was nearly exponential with time, short portions of the curve were nearly linear. For this reason, the temperature at the end of the treatment, designated as treatment temperature, could be obtained quite accurately by extrapolation from the recorder chart, as illustrated in figure 5.

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[6] Nelson, S. O., Soderholm, L. H., and Young, F. D. Determining the Dielectric Properties of Grain. Agr. Engin. 34(9):608-610, Sept. 1953.

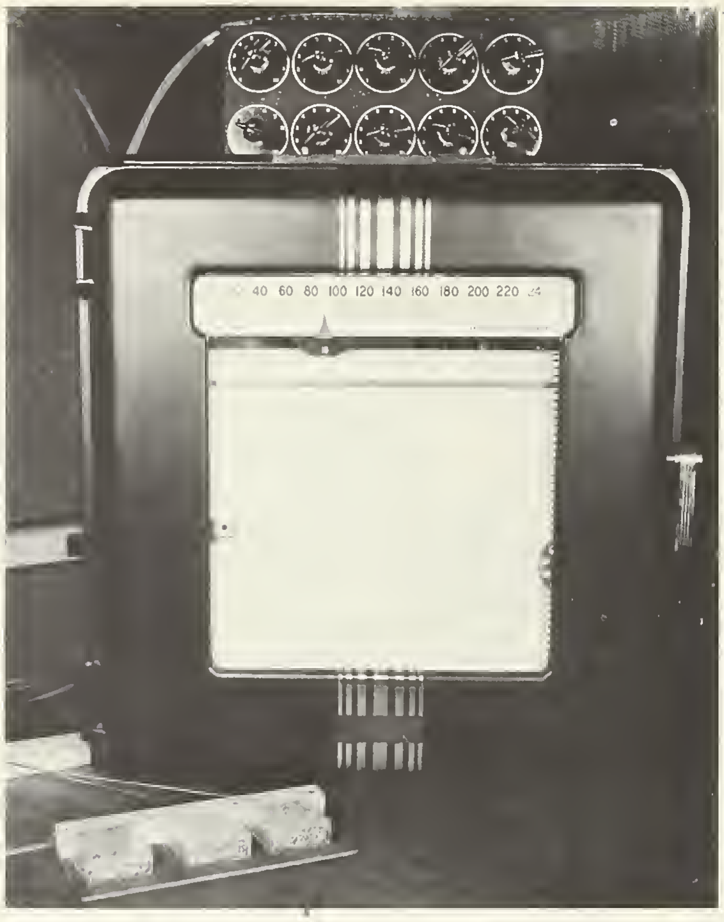

Figure 3.--Temperature recorder, selector switch and sample boxes on thermocouple mount.

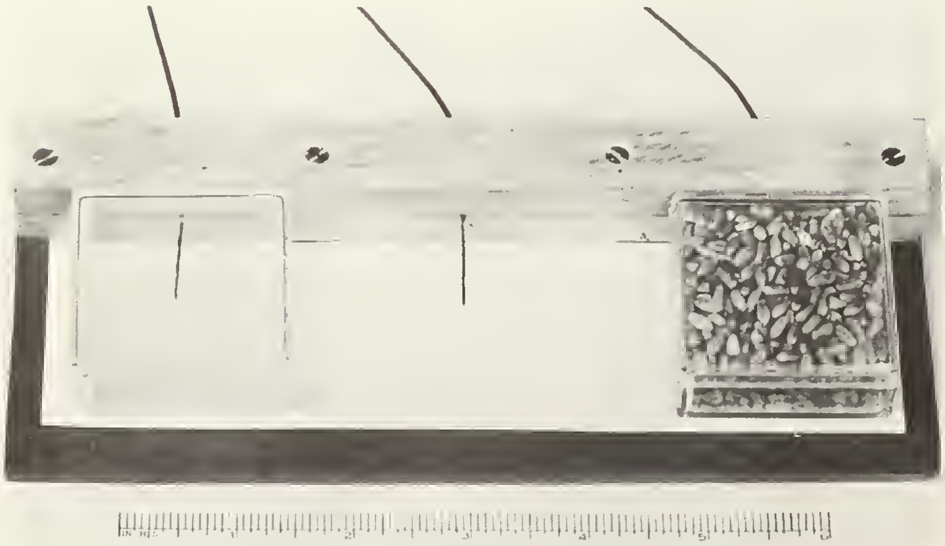

Figure 4.--Close-up of plastic boxes on thermocouple mount.

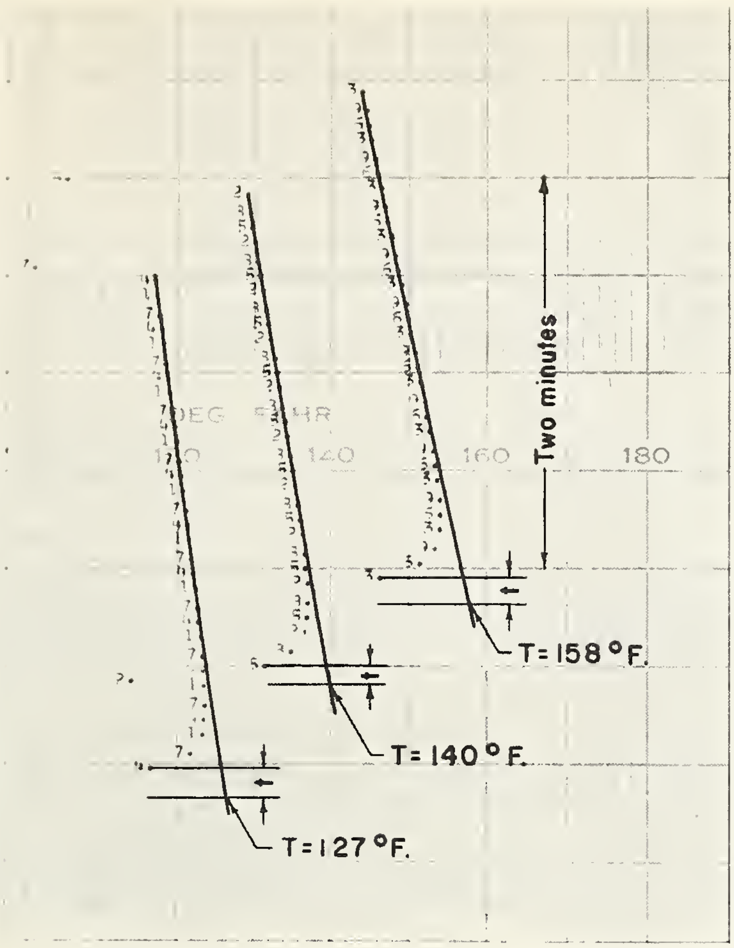

Figure 5.--Temperature-time record on strip-chart, showing elapsed time, t, grain mass temperature, T, and method of extrapolation.

PROCEDURE

Preparation of Samples

Each sample was treated in a polystyrene plastic box (fig. 4).[7] The boxes were approximately 1-7/8 inches square and 3/4 inch high. Actual assembled height was 0.76 in. with a lid thickness of 0.07 in. and a bottom thickness of 0.07 in. Inside volume of the boxes averaged 29.7 ml.

A small hole (No. 60) was drilled in one side of each box to receive the thermocouple for temperature measurements.

The hole was covered with a small patch of masking tape to prevent escape or entry of insects. This tape was removed just before treatment and replaced immediately after the temperature was recorded.

In filling the plastic test boxes, a 29-ml. strike-off cup was used for measuring the wheat to give a constant volume for each box. The wheat shorts presented a problem in that considerable packing and settling occurred after ordinary filling. To overcome this difficulty, each box was filled heaping full before the lid was pressed on. Care was taken to place nearly the same amount in each box. A box was weighed occasionally as a check on the amount in each box.

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[7] Bradley Size No. 3, manufactured by Bradley Industries, 1650-58 North Damen Ave., Chicago 47, Ill.

Ten test insects were placed in each box after the culture medium was introduced. The insects were picked up with a small hand-type aspirator and then dumped into the test box. Of course, the immature forms of the rice weevil and the lesser grain borer were inside the wheat kernels. Therefore, for those tests the infested wheat was measured in the strike-off cup in the same way the noninfested culture wheat was measured for adult insect tests.

The test boxes were transported from Manhattan, Kans., to Lincoln, Nebr., in a passenger car the day following their preparation. A thermometer was kept in the package and observed frequently so that the proper temperature could be maintained. No tests were conducted during the summer because of high temperatures in transit.

Mortality and injury counts were made at the Manhattan laboratory. All test insects were held in the treatment boxes and returned to the culture room after the treatment. Untreated control samples were used as the standard of comparison in each test.

Adult insects were examined 1 or 2 days after treatment and again 1 week after treatment. Some of the adults were examined a third time 2 or 3 weeks after exposure. A three-power, illuminated magnifier was used for the observations. If there were questions regarding life in individual insects, efforts were made to stimulate the insects with air currents or by prodding. Any abnormality in morphology or activity was noted and recorded as an injury.

Samples of the immature test insects were examined several times after treatment. The wheat samples containing immature rice weevils and lesser grain borers were inspected for emergence of adults at weekly intervals, beginning when the insects were 4 weeks old and continuing for 4 weeks in most cases. Emerging adults were carefully examined for injuries and abnormalities and then removed from the sample.

Confused flour beetle larvae were examined 1 week and 3 weeks after treatment for determination of the number of living and dead individuals as well as their stage of development.

The dermestid larvae were examined 2 days, 1, 2, 3, 4, and 5 weeks after treatment to determine the mortality.

Reproduction studies were conducted on a limited scale by placing injured adult survivors in noninfested culture media for 7 days after the HF treatments. In one test, the 7-day period was started after the second mortality count; the two other tests were started after the first mortality count. The adults were removed at the end of the 7-day infestation period, and the samples were incubated for 6 weeks, at which time the progeny were counted.

Treatment Procedure

Sample boxes containing the wheat or wheat shorts and the test insects were placed in the laboratory and allowed to come to temperature equilibrium with the surroundings. In some experiments samples were pre-conditioned at specific temperatures. Values for the different controlled variables were set up on the basis of previous experimental work and dependent upon the particular objectives of each experiment. For each set of treatment conditions, a sufficient number of exposures were selected to provide enough points to determine the mortality curve. In all of these tests, the frequency and field intensity were held constant for any one series and the length of exposure was varied to provide different mortality points. An effort was usually made to obtain complete mortality on the longest exposure. Since field intensity depends upon the dielectric properties of the sample, and the electrode voltage, it was frequently necessary to calculate the desired electrode voltage to be used after measuring the dielectric properties of the grain before starting the treatment. This was calculated according to the following equation, which is valid when the treatment electrodes are in contact with the top and bottom of the box:

$$V = E\left(d_1 + d_2 \frac{\varepsilon_1}{\varepsilon_2}\right) \qquad \text{(Equation 3)}$$

where V = electrode voltage to be used, E = desired field intensity, d_1 = thickness of the layer of grain, d_2 = total thickness of the polystyrene, ε_1 = permittivity or dielectric constant of the grain, and ε_2 = permittivity or dielectric constant of the polystyrene.

In general, 10 boxes, all replicates, were used for each exposure. There were 10 test insects per box, so the average mortality or injury for the exposure was for 100 insects.

The boxes were therefore prepared for treatment in groups of 10. The person recording the data removed the masking tape from the holes in the sides of the boxes and set the group up for treatment. The next person placed the boxes on the electrode of the high-frequency oscillator, closed the lid of the machine to bring the second electrode into contact with the top of the box, and applied the power for treatment. At the end of the set time interval, the lid automatically raised and the sample was immediately placed on the thermocouple mount for temperature recording. A stopwatch was used to time the interval between the end of the treatment and the printing of the first appropriate point by the temperature recorder. The thermocouple reading and the time interval were then spoken and the data recorded by the first person. A third person was usually available to take the sample when it was removed from the thermocouple mount, replace the masking tape over the hole in the box, and apply a numbered label to the top of the box. The labels were made by stamping numbers on strips of masking tape with a numbering machine and cutting them apart with a knife or razor blade. The room temperature was recorded on the chart.

List of Experiments

Table 1 lists the experiments conducted in this study. The experiment numbers in the table identify the insect species, stage, and numerical order of the test and are used throughout the report. Culture media, treatment conditions, the moisture content, and dielectric properties of the culture medium used in each experiment are also recorded.

RESULTS OF THE TREATMENTS

Mortality of Test Insects

The results of the tests are summarized in tables 3-25. For each experiment, live, injured, and dead insects were counted for each sample after the indicated periods following treatment. For each exposure, these counts of the 10 replicates were averaged. Individual counts and averages were then converted to percentages which appear in the summary tables. Mortality and emergence curves for all of the experiments appear in figures 6 through 29. These curves were plotted from the information in the summary tables. Lethal temperatures for 50, 80, 90, and 100 percent mortalities as taken from the curves are tabulated for each experiment in table 19. In examining any of these curves or tables, it should be kept in mind that the treatment temperatures shown are the temperatures which the grain or treatment media reached upon treatment and do not necessarily represent the temperatures in the insects. Mortality data might be plotted against either time of exposure or temperature. Since exposure times vary with the frequency and field intensity, the temperature of the grain or of the shorts has been chosen as the independent variable common to all treatments for plotting the results. Exposure times for any particular treatment may readily be found in the summary tables.

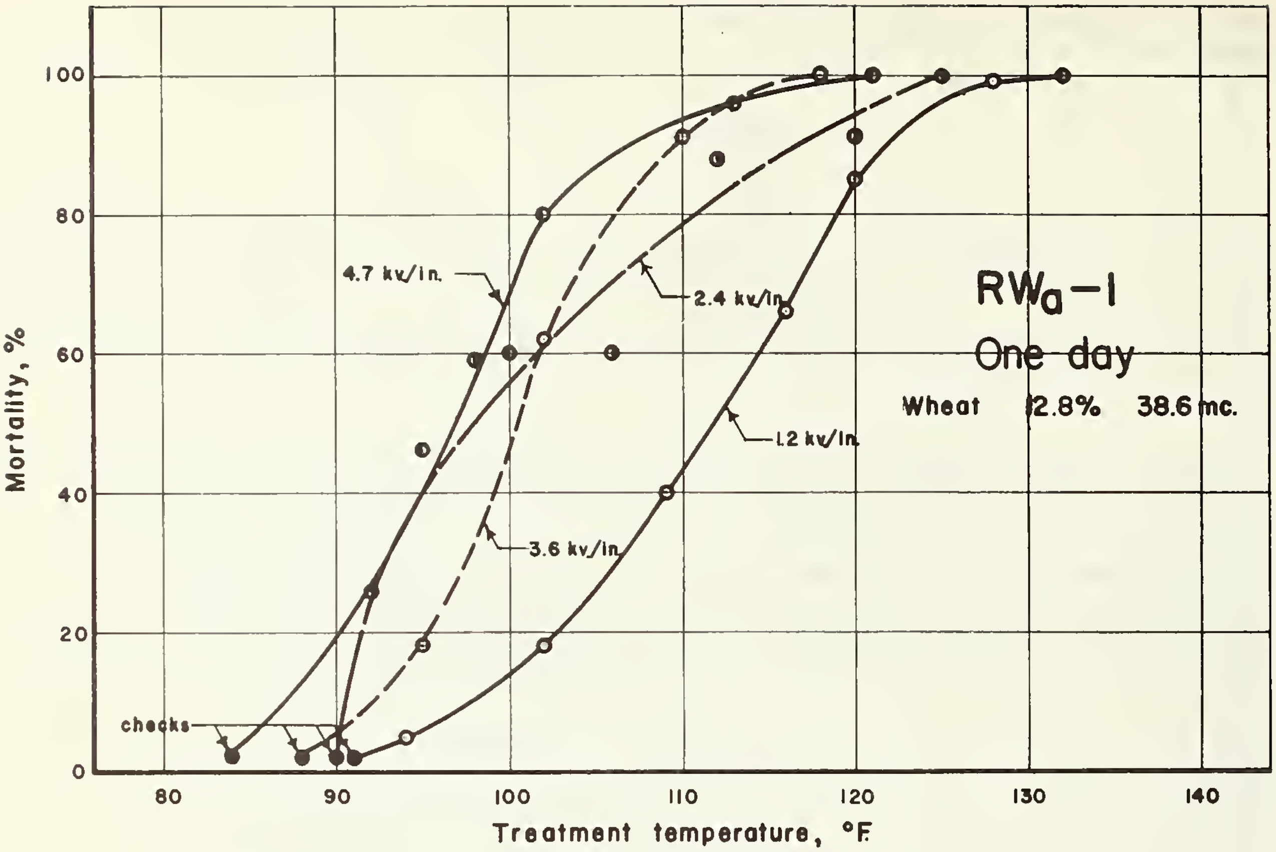


Figure 6. --Mortality of adult rice weevils 1 day after high-frequency treatment.

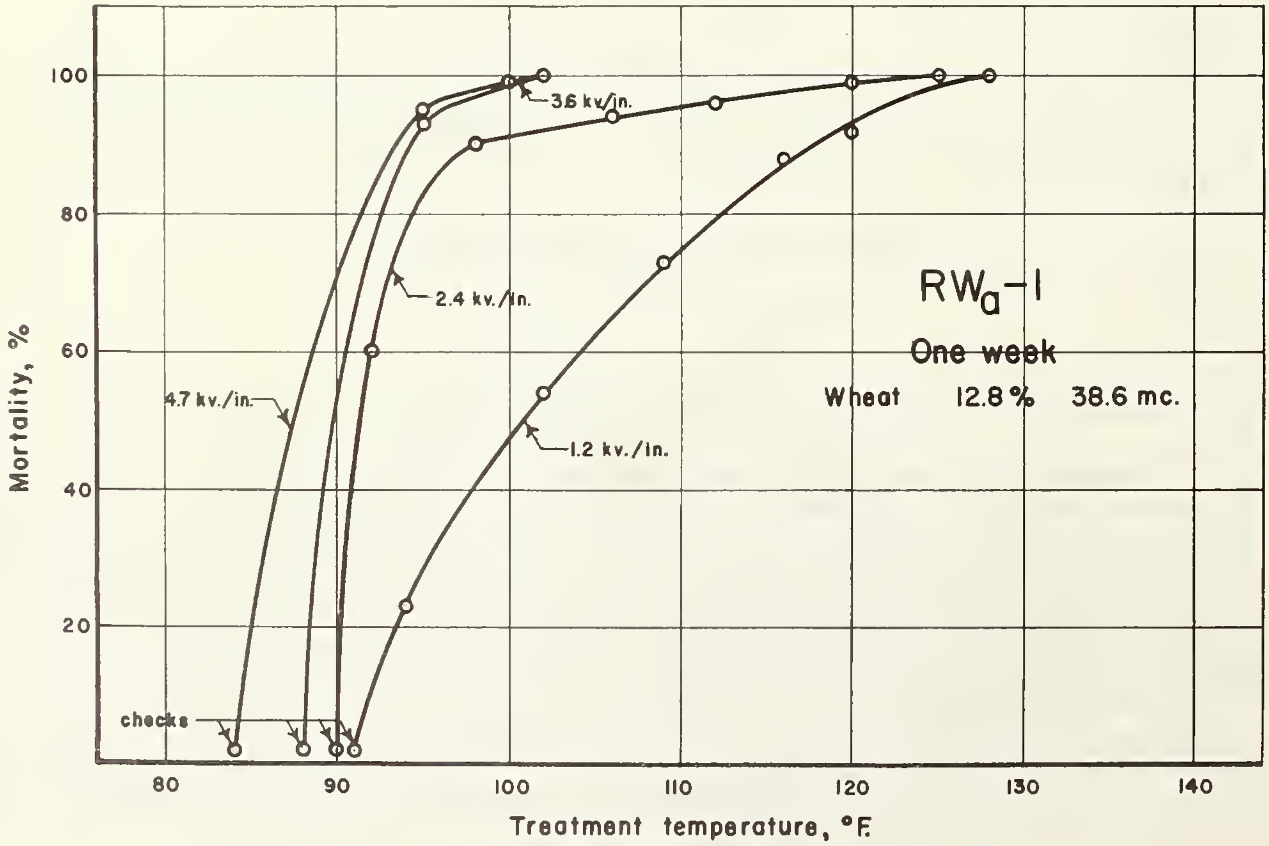


Figure 7. --Mortality of adult rice weevils 1 week after high-frequency treatment.

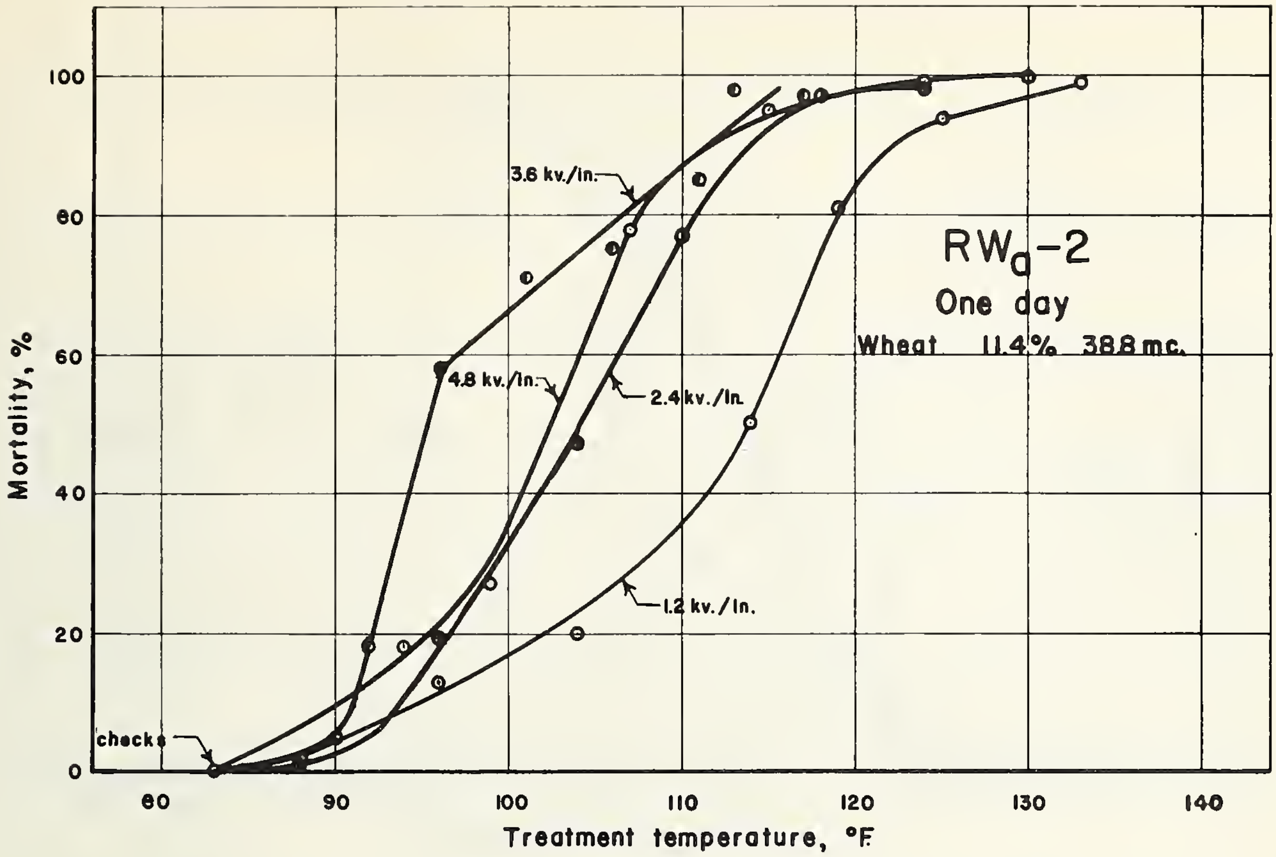


Figure 8.--Mortality of adult rice weevils 1 day after high-frequency treatment.

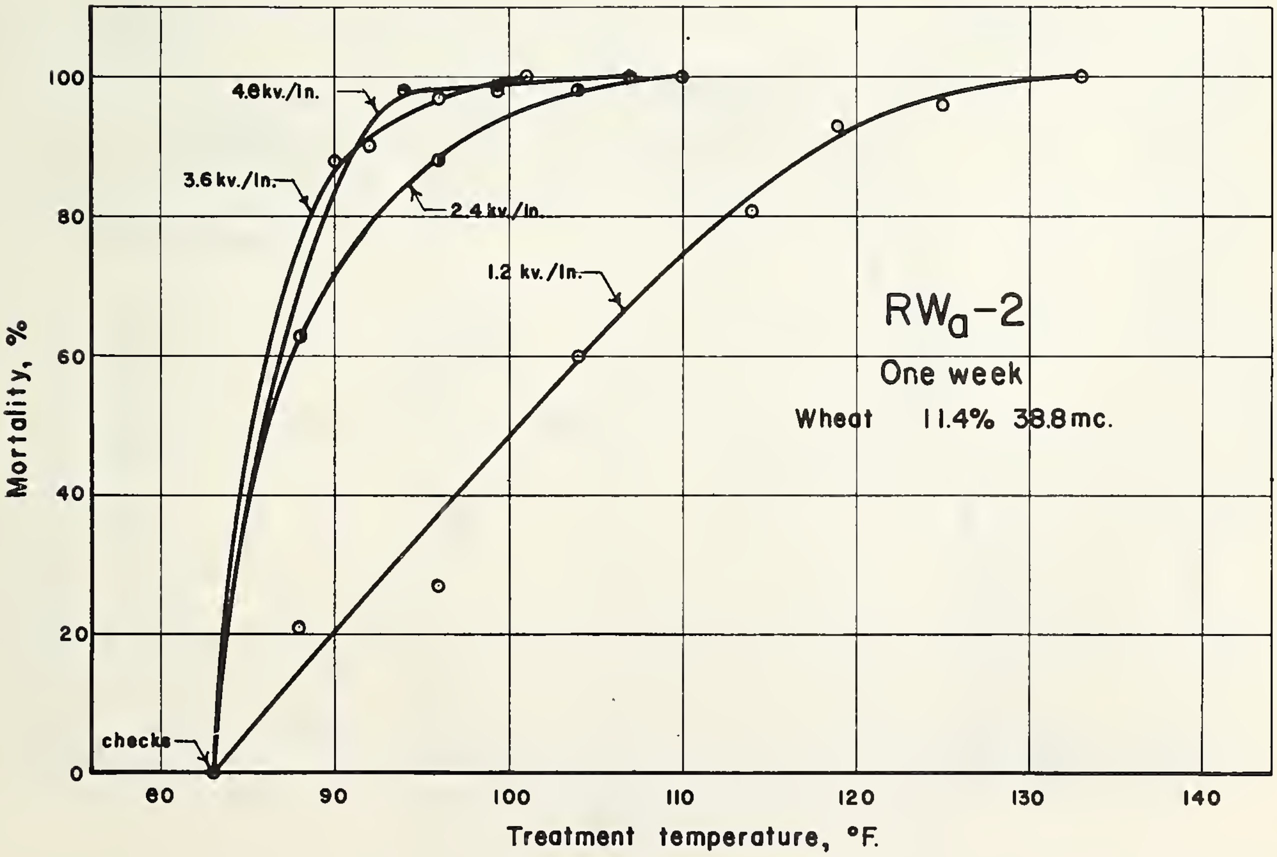


Figure 9.--Mortality of adult rice weevils 1 week after high-frequency treatment.

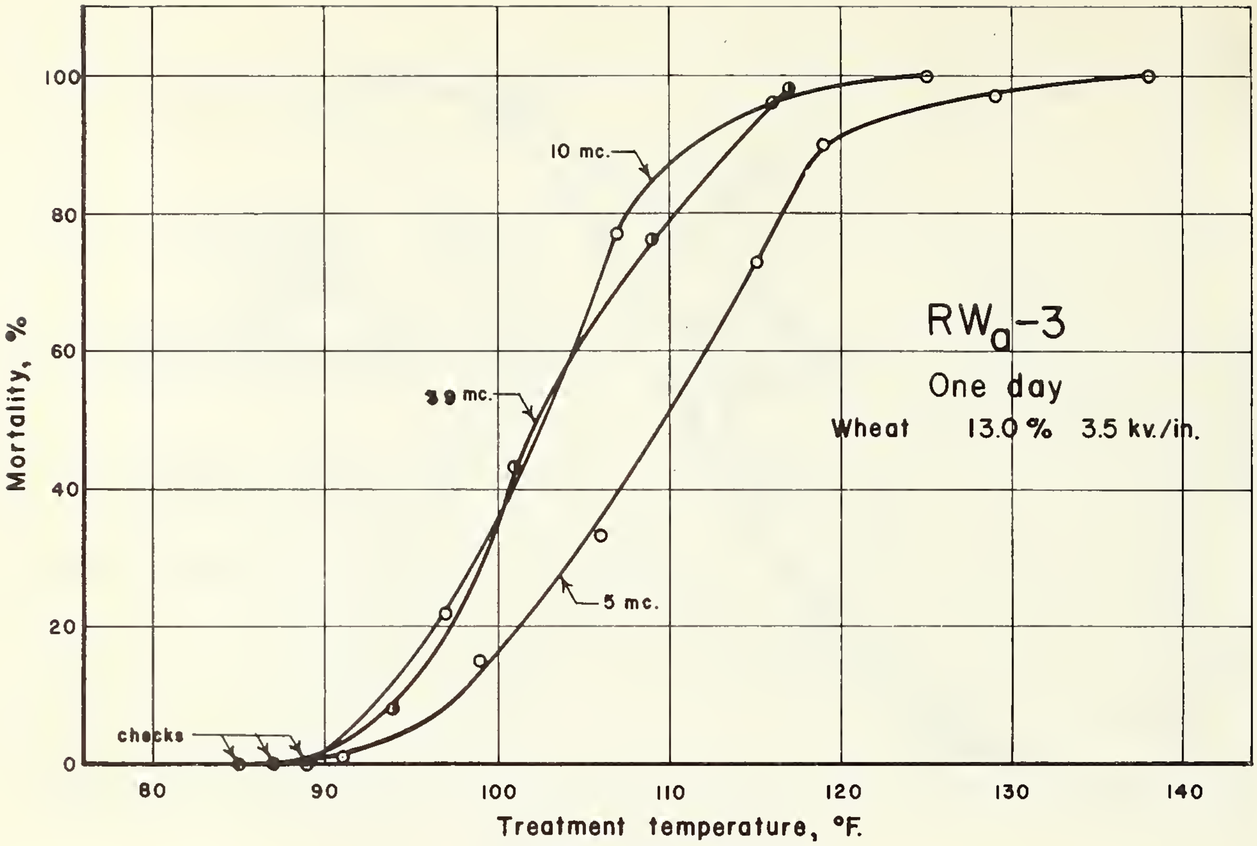


Figure 10.--Mortality of adult rice weevils 1 day after high-frequency treatment.

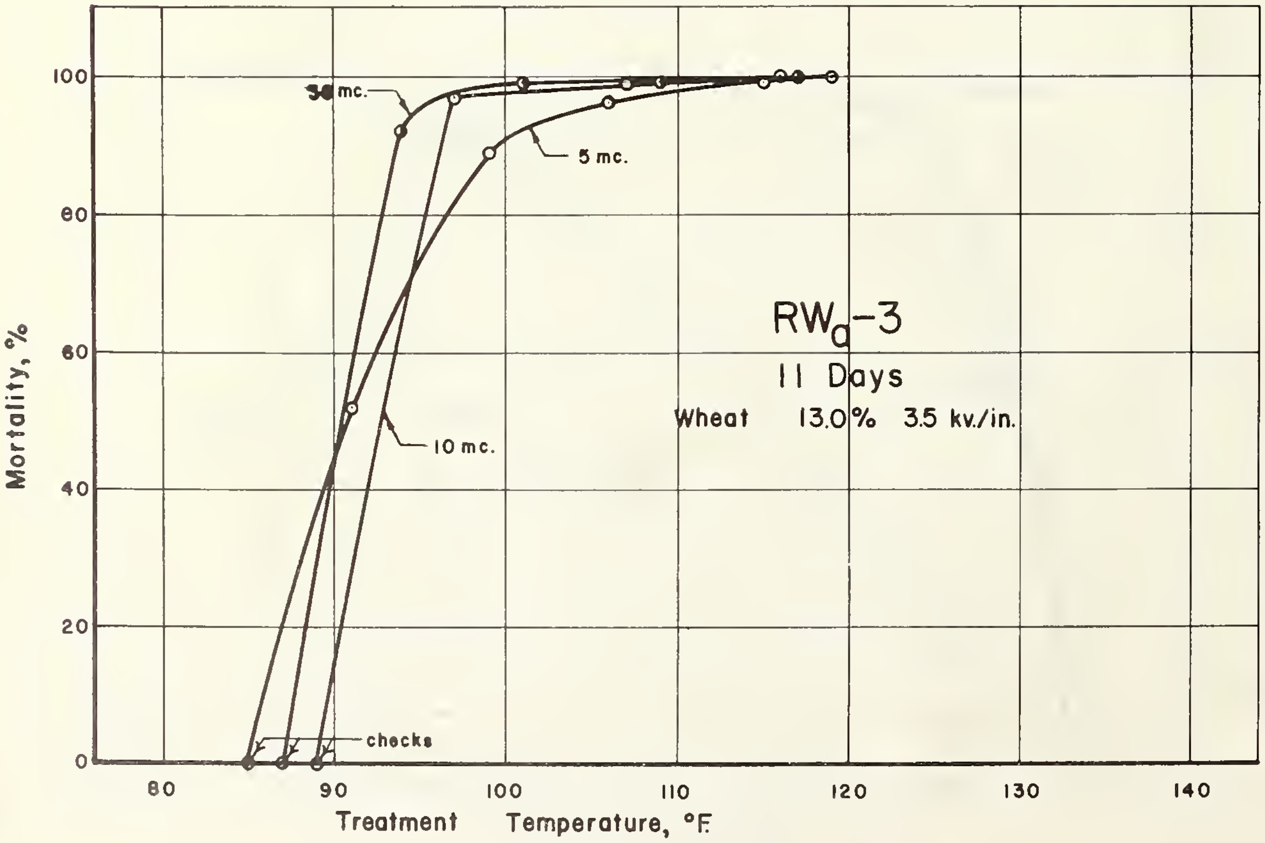


Figure 11.--Mortality of adult rice weevils 11 days after high-frequency treatment.

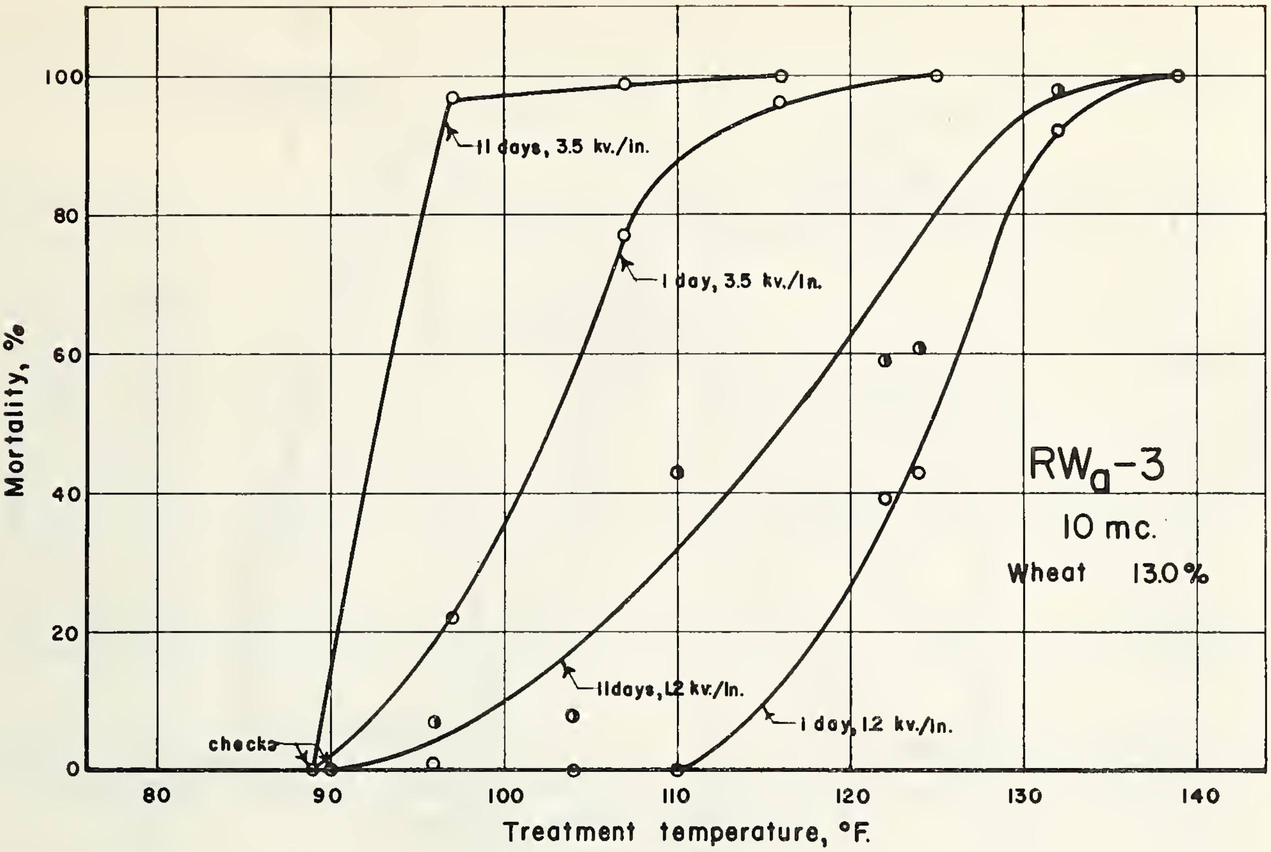


Figure 12. --Mortality of adult rice weevils one and 11 days after high-frequency treatment.

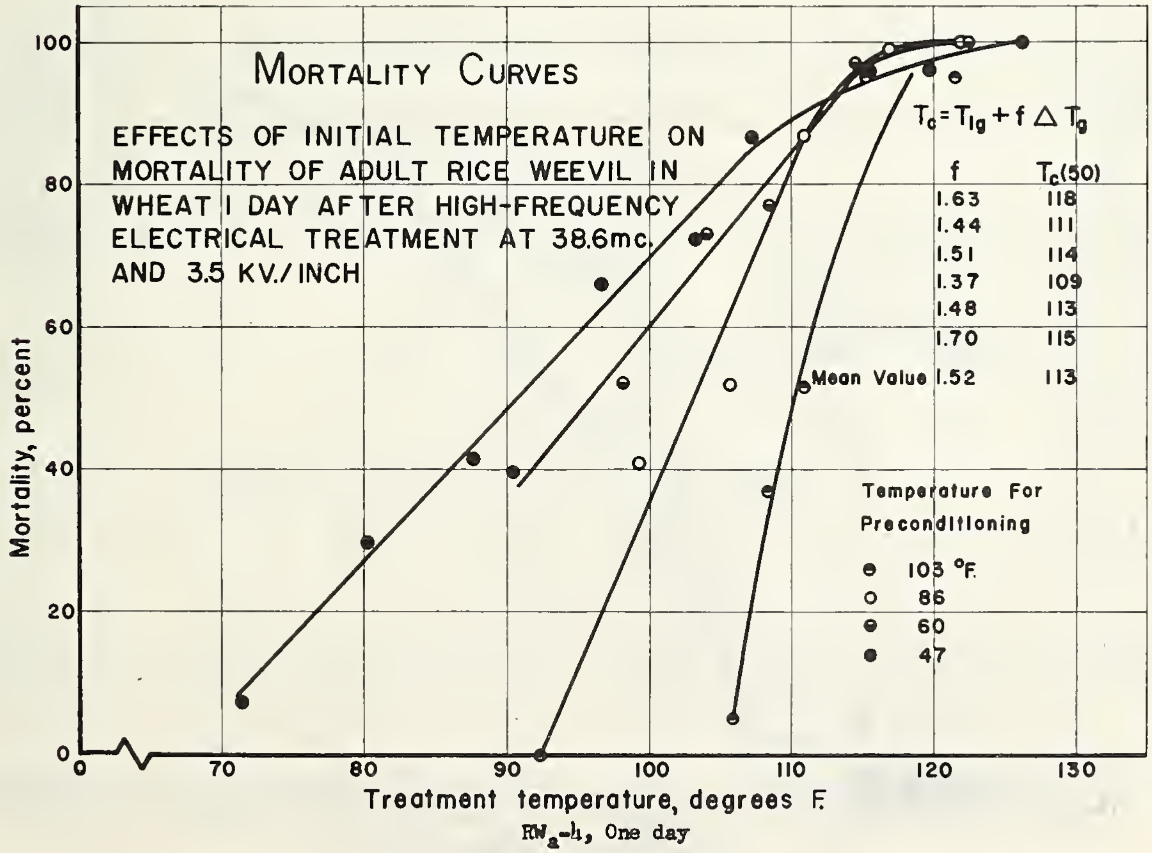


Figure 13. --Mortality of adult rice weevils 1 day after high-frequency treatment. The insects and wheat were preconditioned at different temperatures.

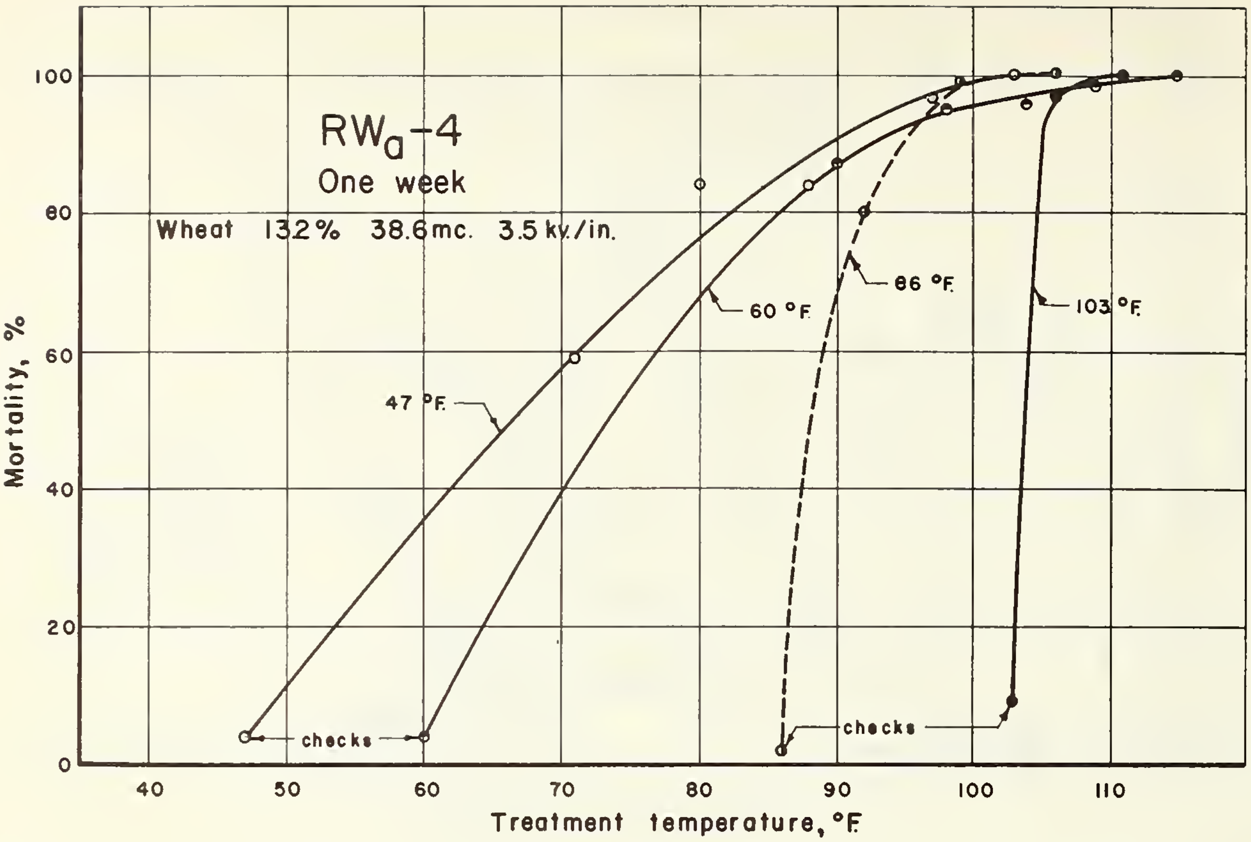


Figure 14.--Mortality of adult rice weevils 1 week after high-frequency treatment. The insects and wheat were preconditioned at different temperatures.

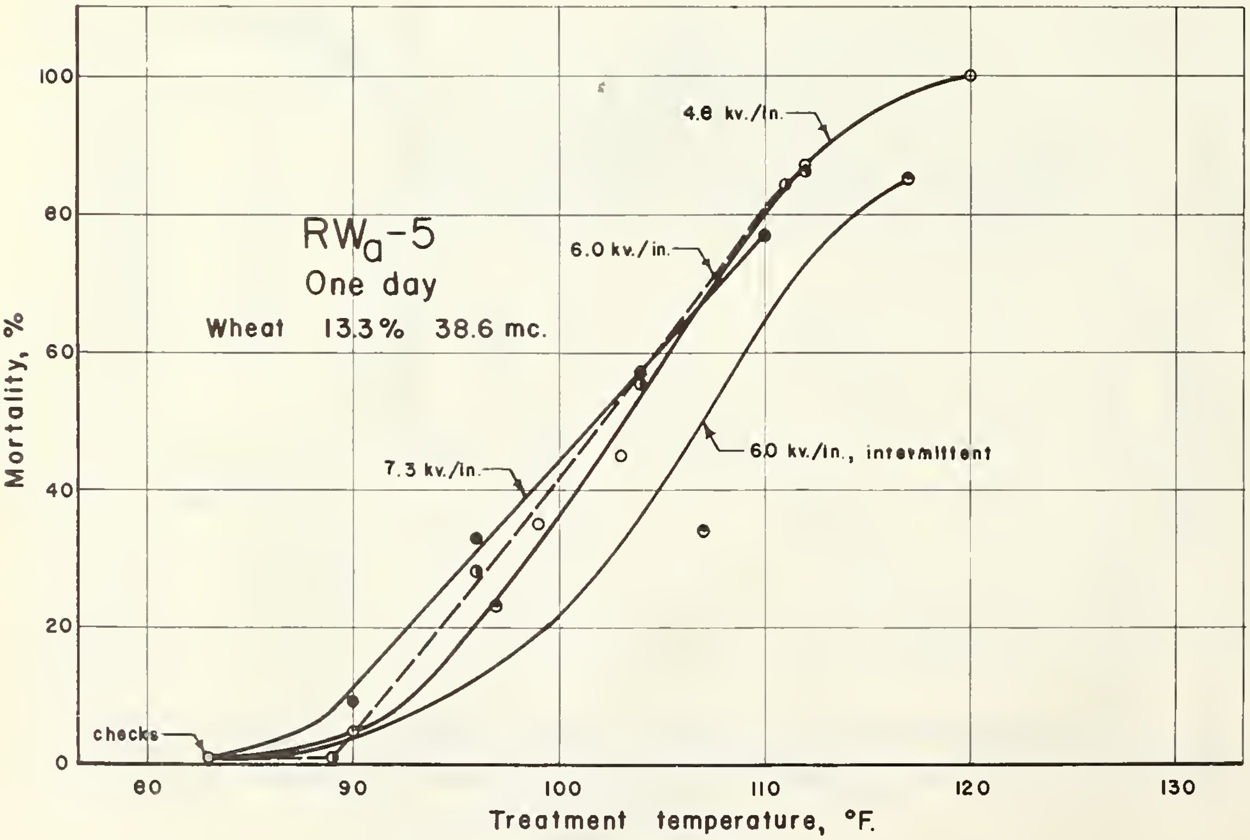


Figure 15.--Mortality of adult rice weevils 1 day after high-frequency treatment.

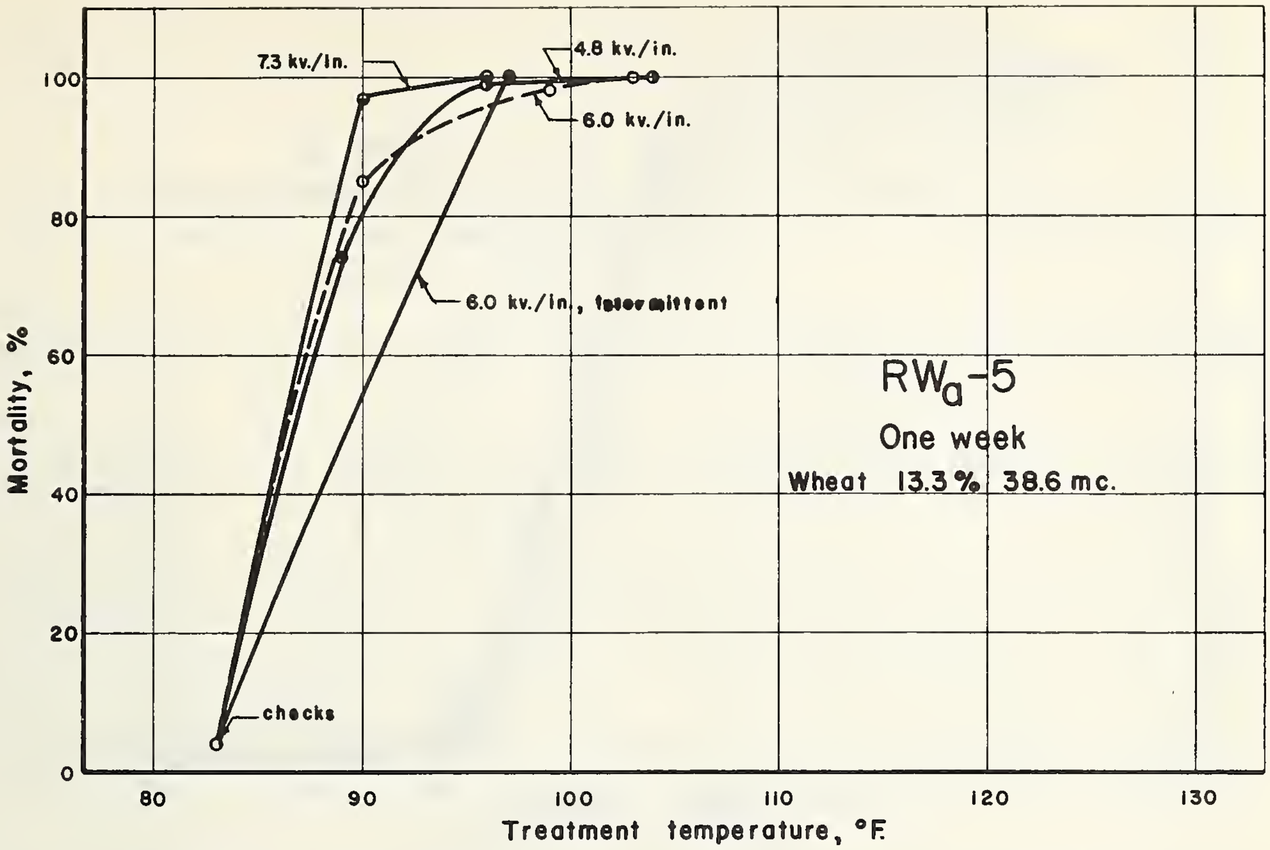


Figure 16.--Mortality of adult rice weevils 1 week after high-frequency treatment.

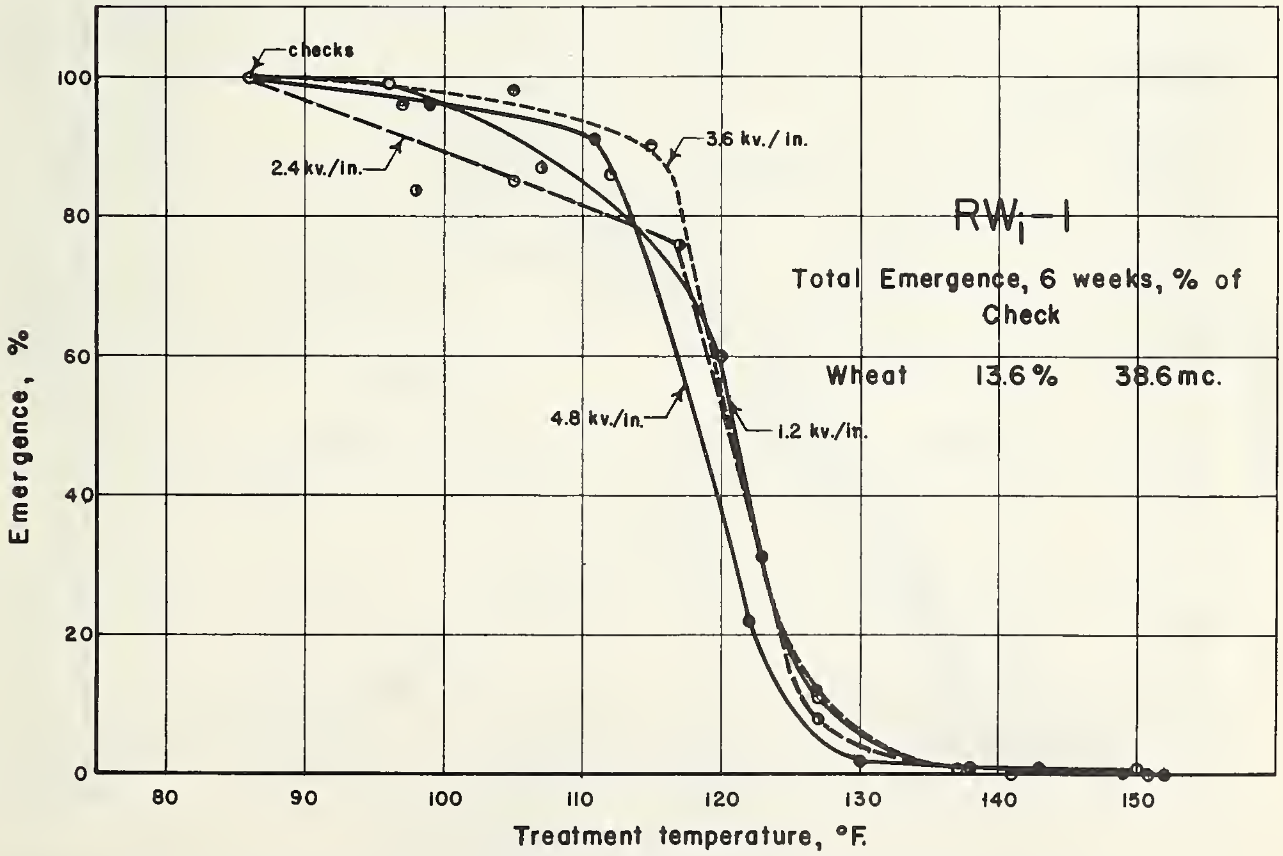


Figure 17.--Rice weevil emergence after high-frequency treatment of mixed immature stages.

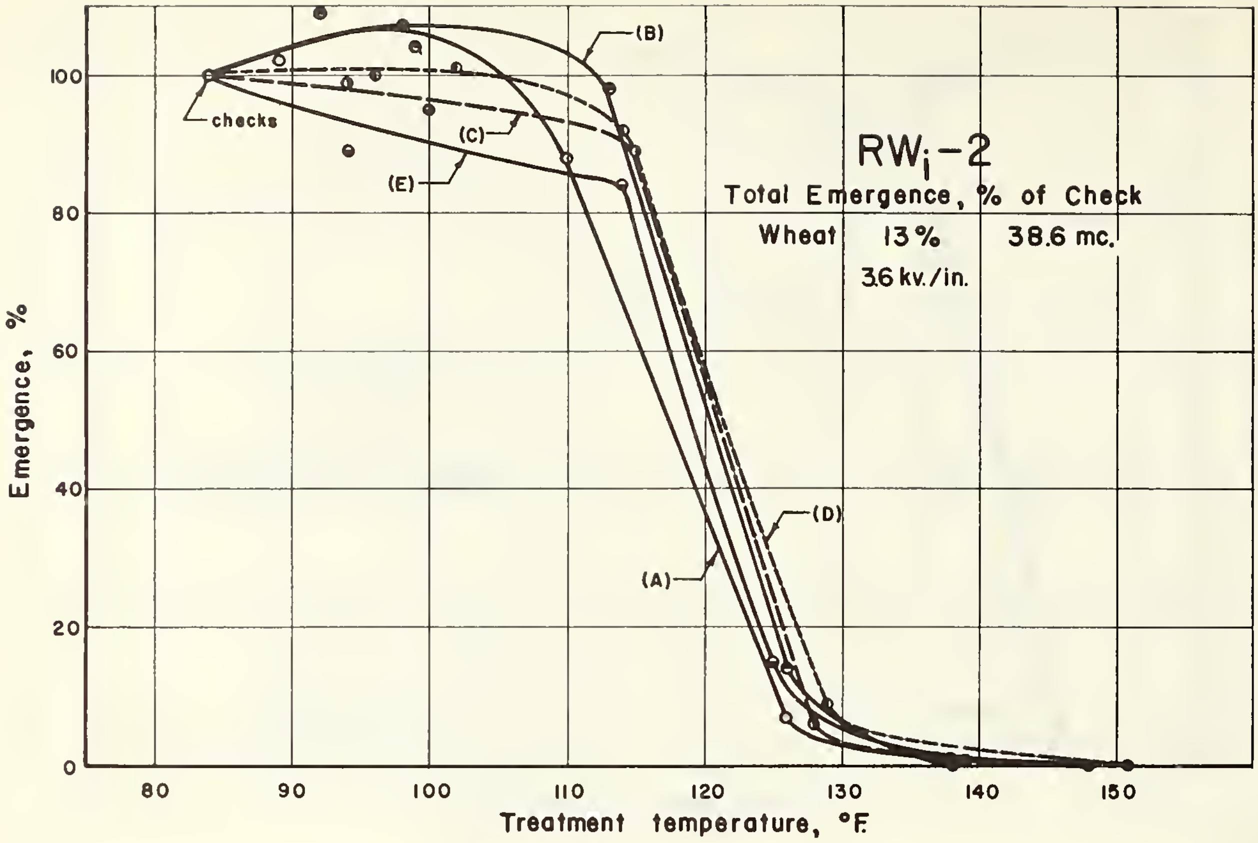


Figure 18.--Rice weevil emergence after high-frequency treatment of selected immature stages. A: 0.5-4 days old (eggs); B: 5-12 days old (eggs and young larvae); C: 12-19 days old (larvae); D: 19-26 days old (older larvae and few pupae); E: 26-33 days old (pupae and few older larvae).

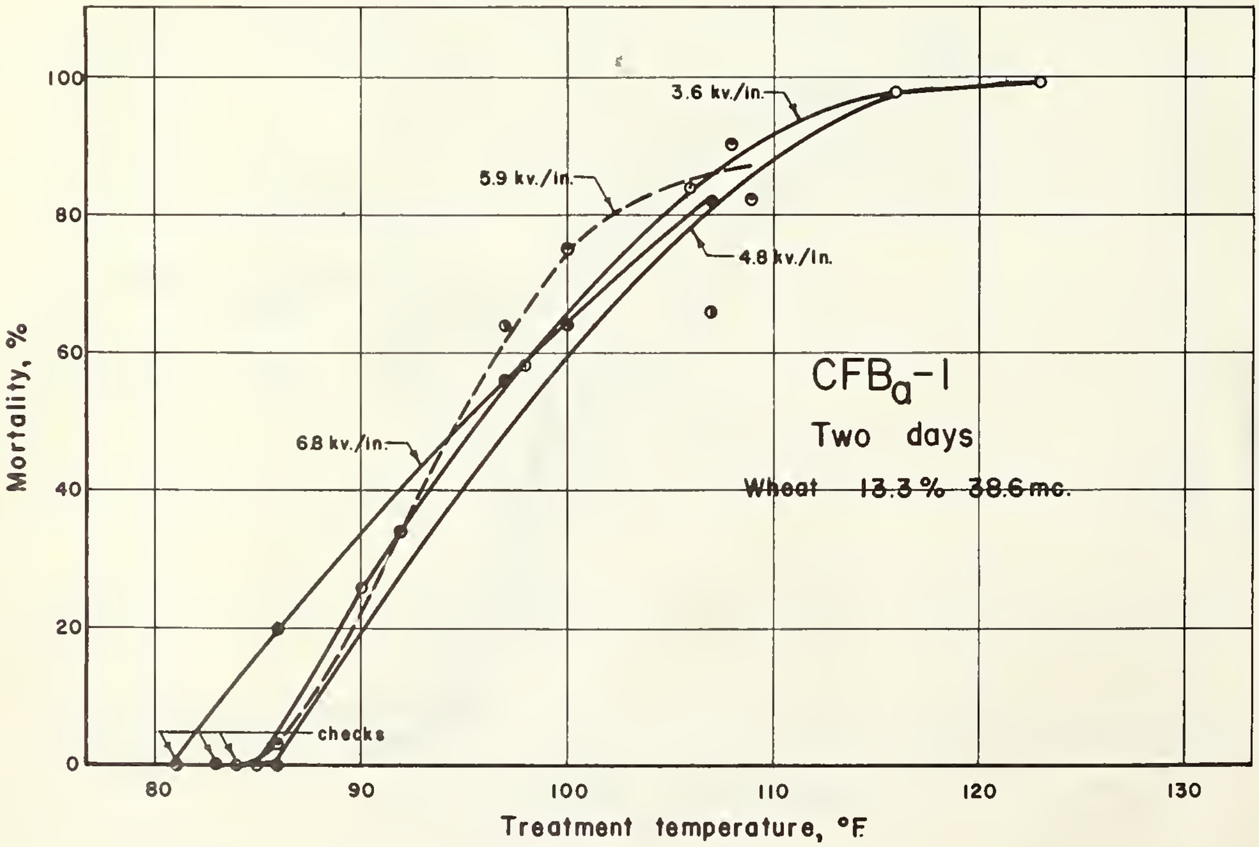


Figure 19.--Mortality of adult confused flour beetles 2 days after high-frequency treatment.

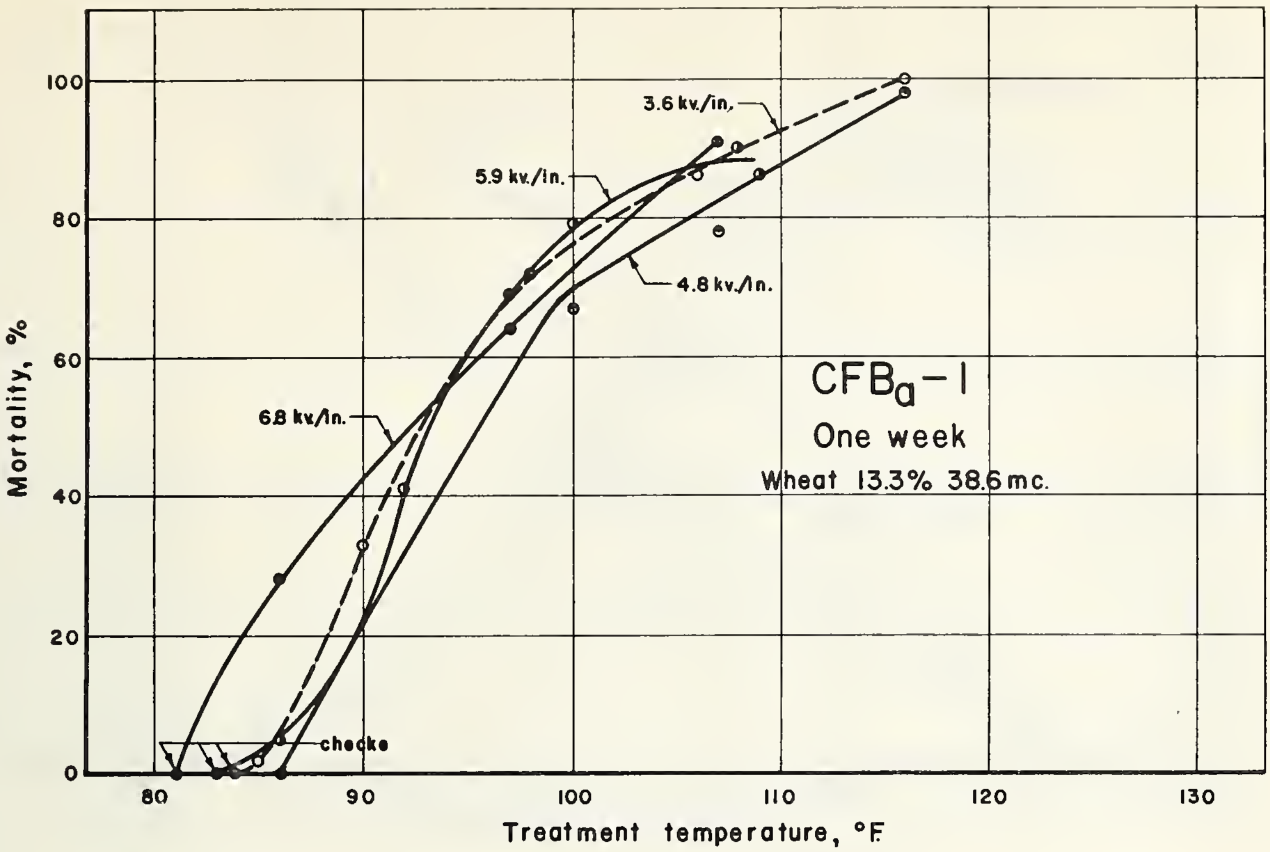


Figure 20.--Mortality of adult confused flour beetles 1 week after high-frequency treatment.

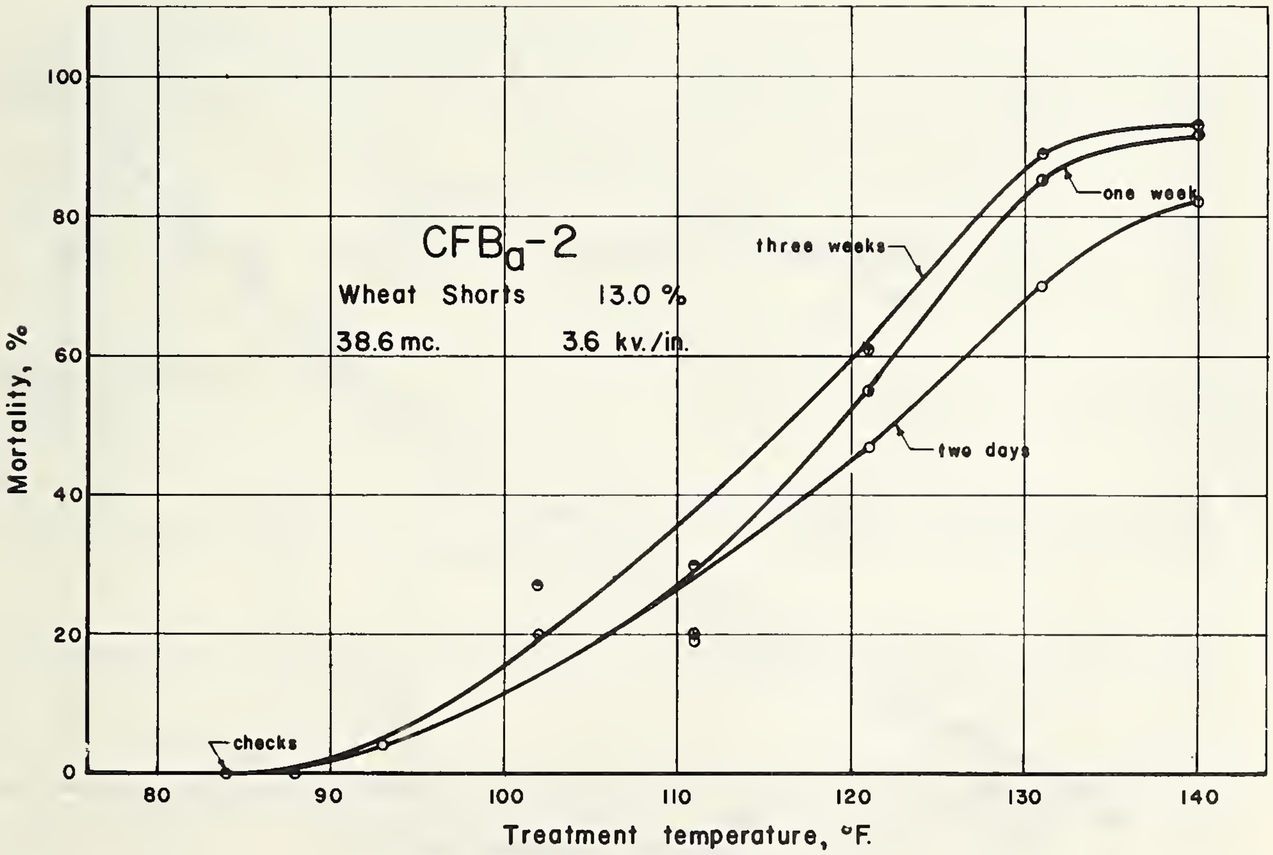


Figure 21.--Mortality of adult confused flour beetles 1 day, 1 week, and 3 weeks after high-frequency treatment at a moderate field intensity.

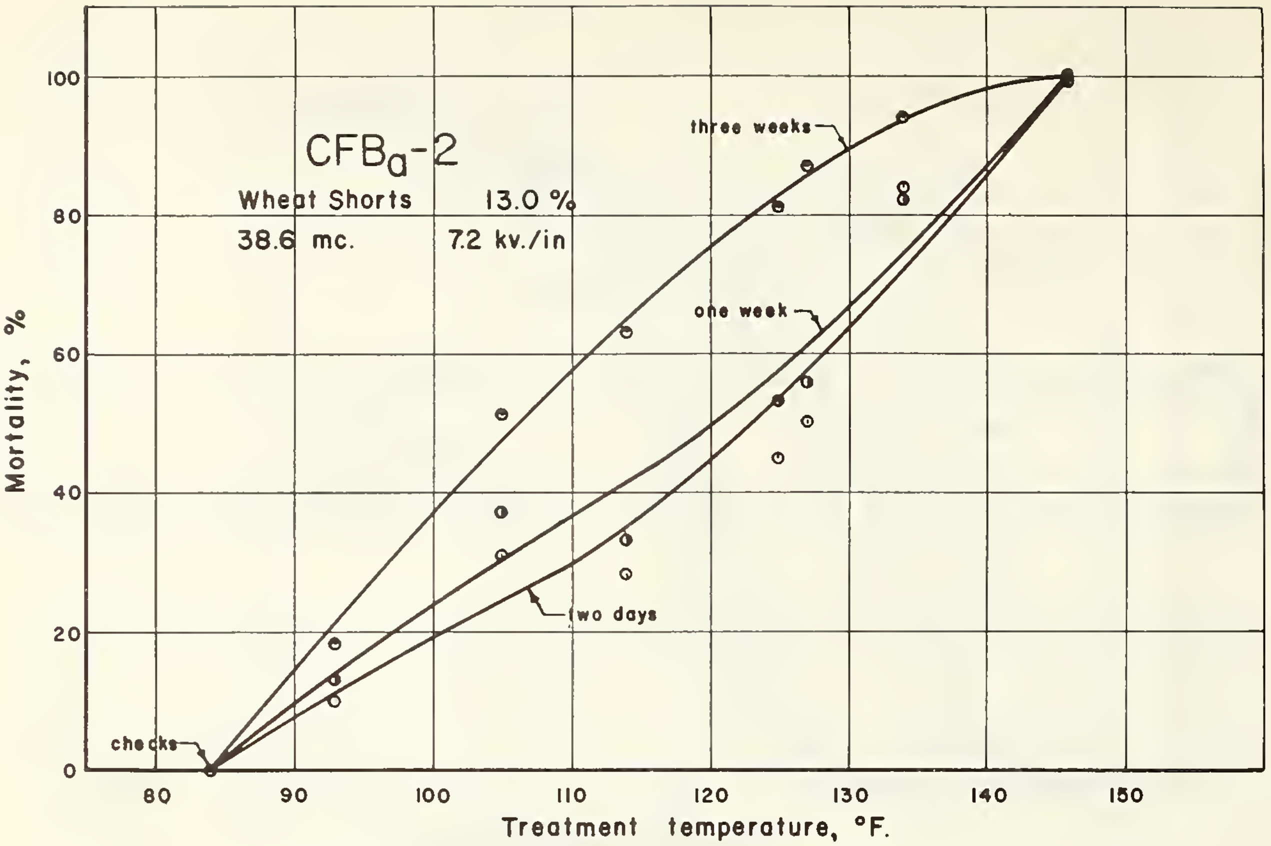


Figure 22. --Mortality of adult confused flour beetles 1 day, 1 week, and 3 weeks after high-frequency treatment at a high field intensity.

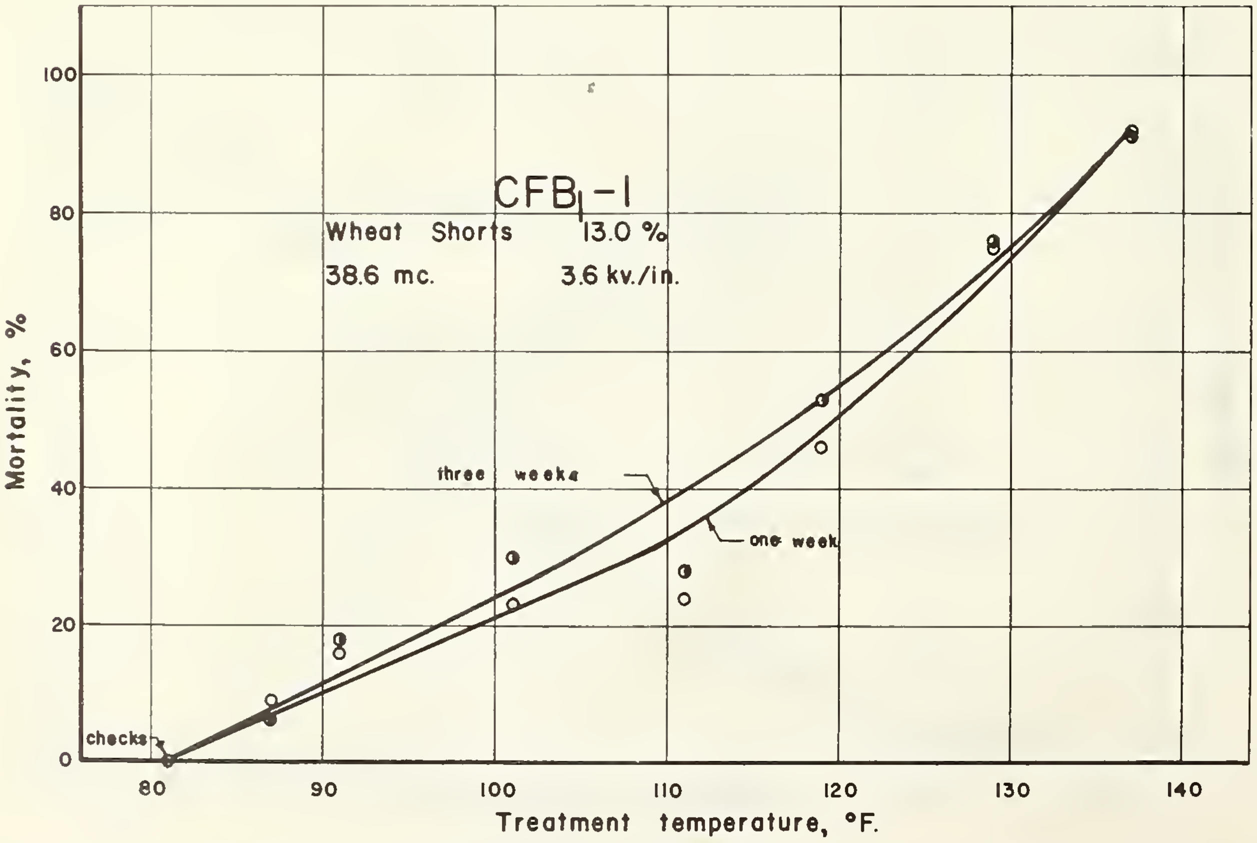


Figure 23. --Mortality of confused flour beetle larvae 1 week and 3 weeks after high-frequency treatment.

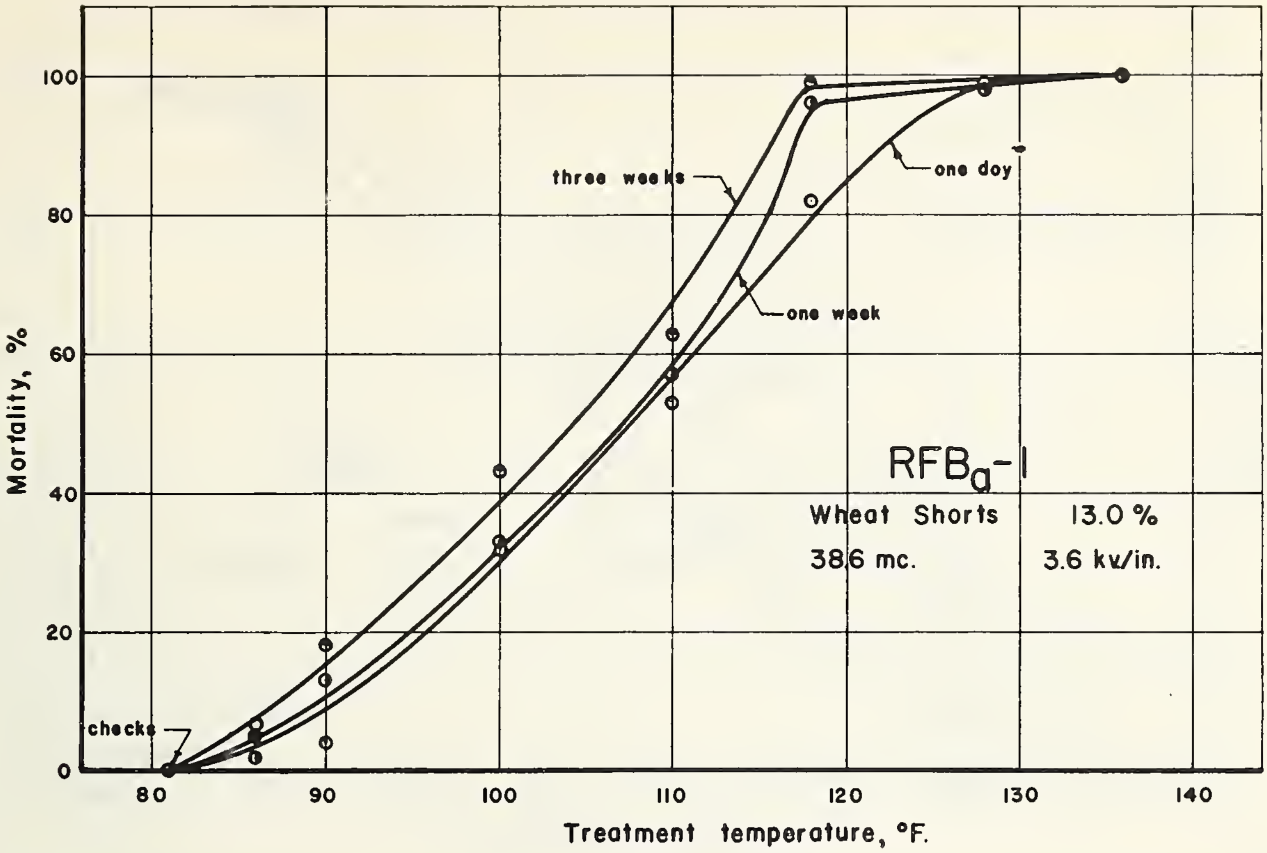


Figure 24. --Mortality of adult red flour beetles 1 day, 1 week and 3 weeks after high-frequency treatment.

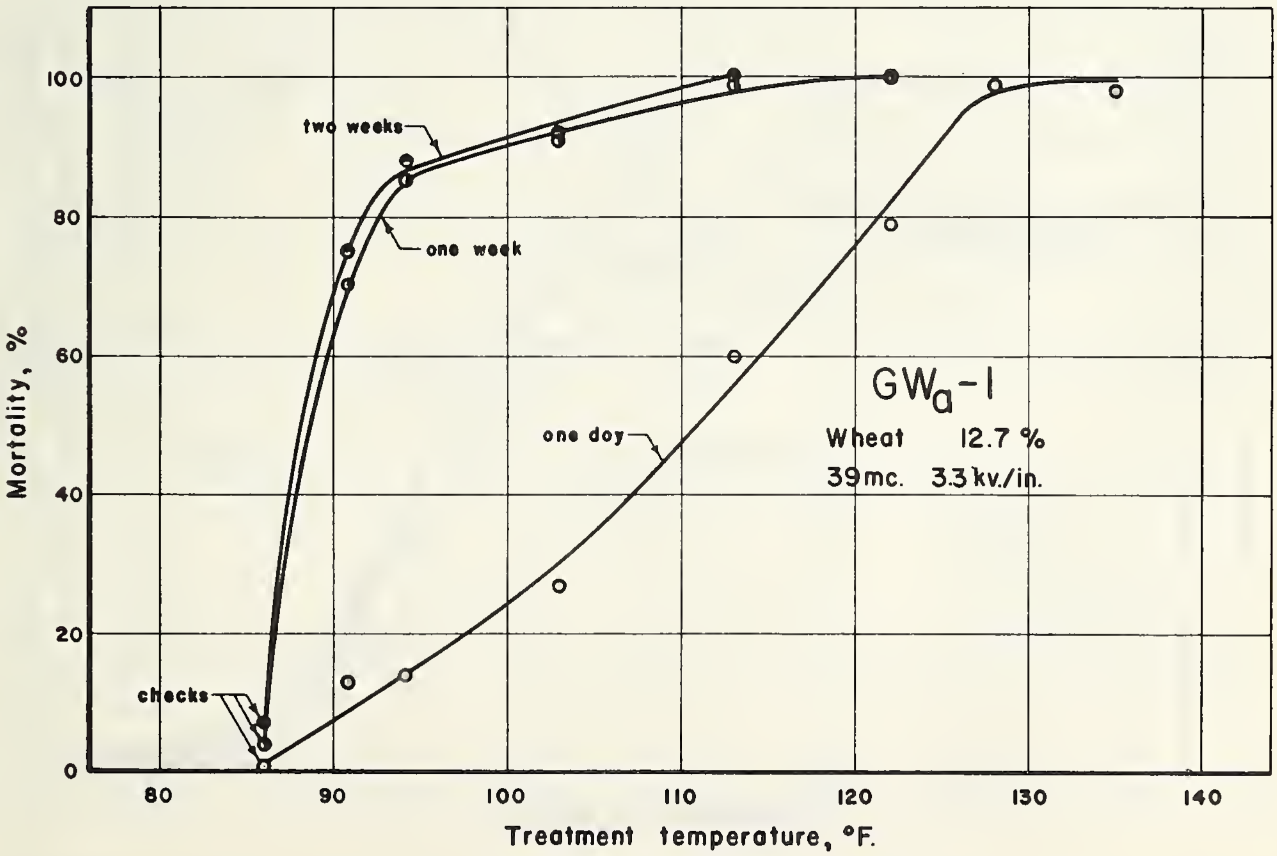


Figure 25. --Mortality of adult granary weevils 1 day, 1 week, and 3 weeks after high-frequency treatment.

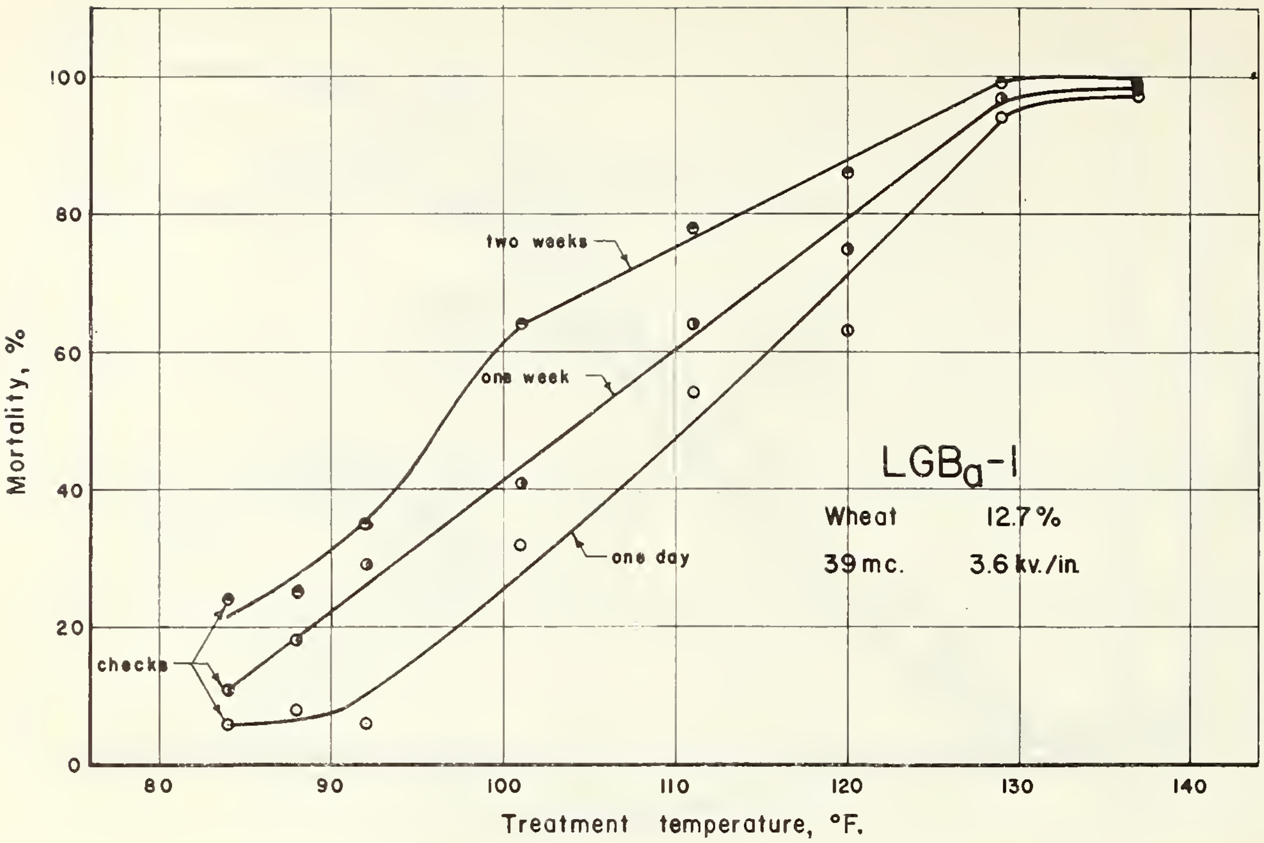


Figure 26. --Mortality of adult lesser grain borers 1 day, 1 week, and 2 weeks after high-frequency treatment.

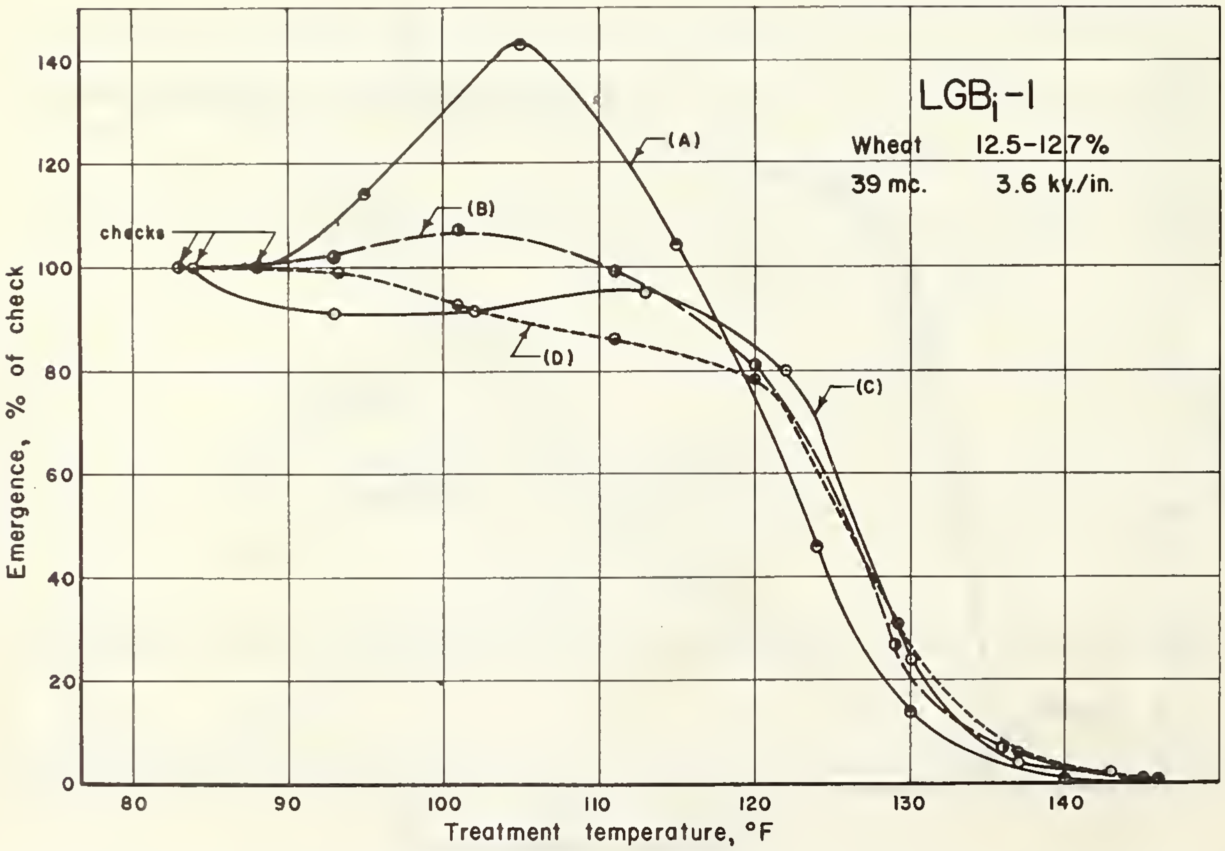


Figure 27. --Emergence of lesser grain borers after high-frequency treatment of immature stages. Predominant ages: A = 0-5 days, B = 2 weeks, C = 3 weeks, and D = 4 weeks.

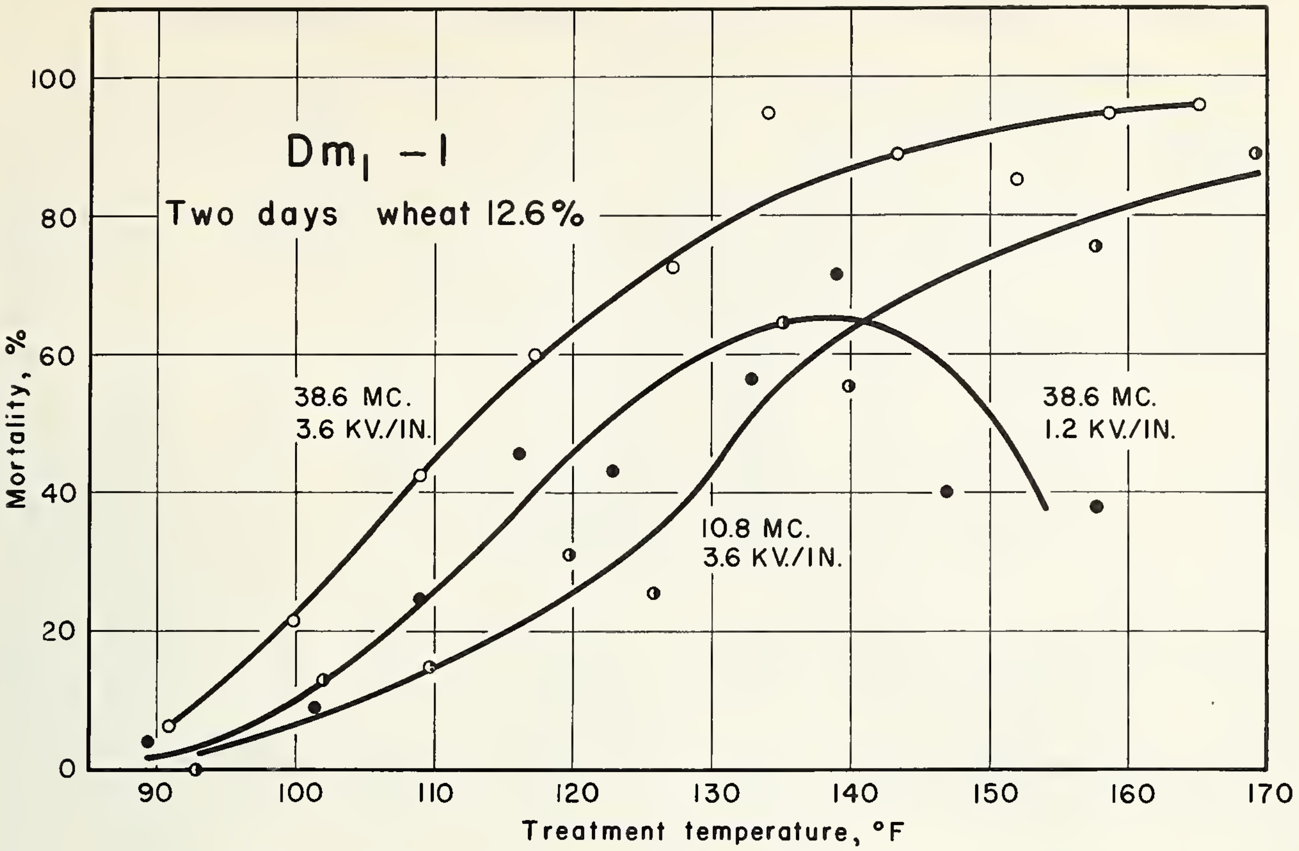


Figure 28.--Mortality of dermestid larvae (Trogoderma parabile Beal) 2 days after HF treatment.

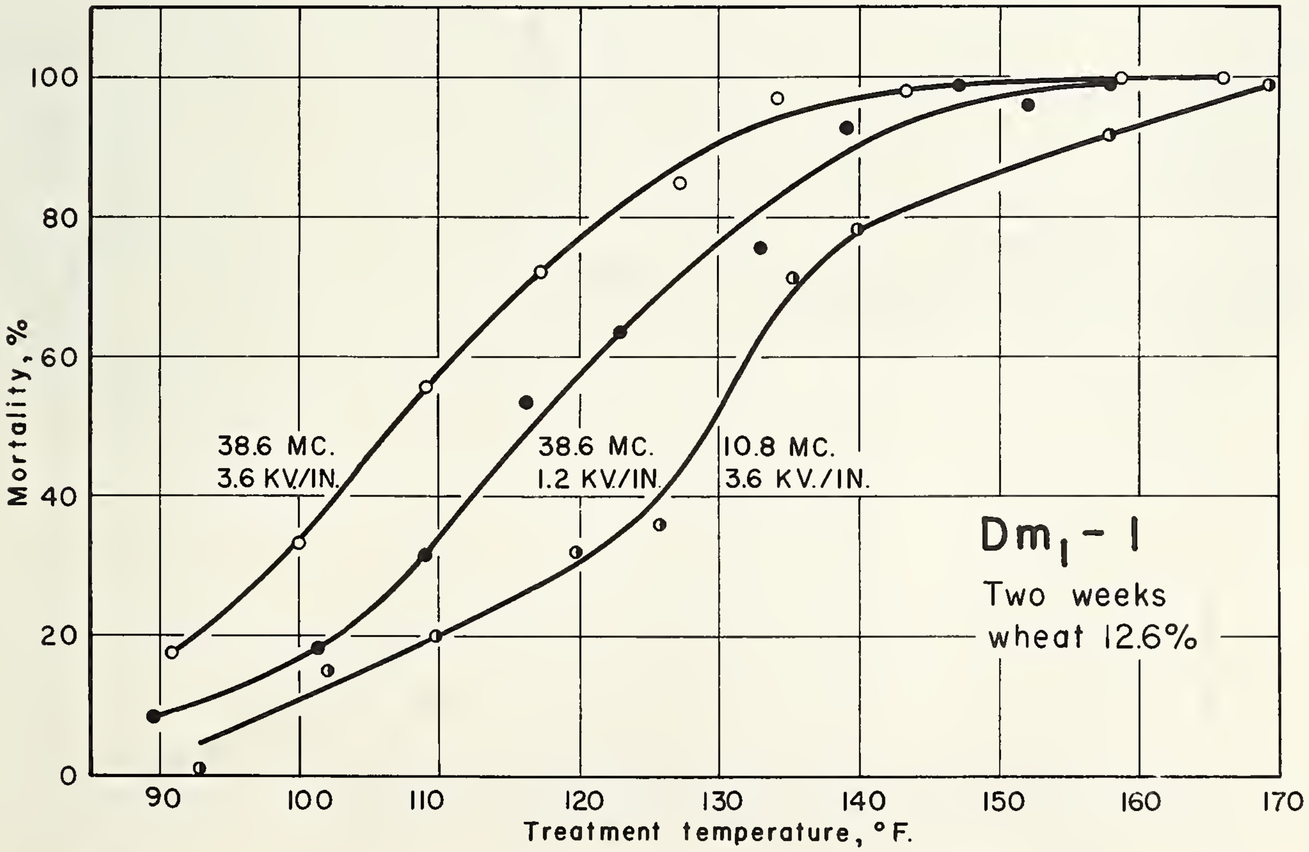


Figure 29.--Mortality of dermestid larvae (Trogoderma parabile Beal) 2 weeks after HF treatment.

TABLE 1.--Setup of 18 experiments to determine effect of high-frequency electrical treatments on stored grain insects

Insect and experiment code	Culture medium		HF treatment		Culture medium properties			
	Material	Moisture content	Frequency	Field intensity	Permittivity	Dielectric loss factor	Loss tangent	Conductivity
		Percent	Mc./sec.	Kv./m.				Micro-ohms
Rice weevil adults:								
RW_a-1	Wheat	12.8	38.6	1.2,2.4,3.6,4.7	4.2	0.50	0.12	11.2
RW_a-2	Wheat	11.4	38.8	1.2,2.4,3.6,4.8	3.9	.49	.13	10.9
RW_a-3	Wheat	13.0	5.0	5,39 mc.	4.6	.37	.08	1.0
RW_a-3	Wheat	13.0	10.0	3.5,10 mc.	4.5	.41	.09	2.2
RW_a-3	Wheat	13.0	39.0	3.5,1.2	4.3	.54	.13	12.0
RW_a-4	Wheat	13.2	38.6	3.5 (4 initial temps.)	4.2	.47	.11	10.5
RW_a-5	Wheat	13.3	38.6	4.8,6.0,7.3(2 sec. Pulses at 6.0)	4.2	.51	.12	10.9
Immature rice weevils:								
RW_i-1	Wheat	13.6	38.6	1.2,2.4,3.6,4.8	4.3	.49	.11	10.9
RW_i-2	Wheat	12.8	38.6	3.6	4.1	.51	.12	10.9
Confused flour beetle adults:								
CFB_a-1	Wheat	13.3	38.6	3.6,4.8,5.9,6.8	4.2	.51	.12	10.9
CFB_a-2	Wheat shorts	13.0	38.6	3.6,7.2	2.8	.38	.14	8.2
Confused flour beetle larvae:								
CFB_l-1	Wheat shorts	13.0	38.6	3.6	2.8	.38	.14	8.2
Red flour beetle adults:								
RFB_a-1	Wheat shorts	13.0	38.6	3.6	2.8	.38	.14	8.2
Granary weevil adults:								
GW_a-1	Wheat	12.6	38.6	3.6	4.2	.51	.12	10.8
Lesser Grain Borer adults:								
LGB_a-1	Wheat	12.6	38.6	3.6	4.2	.51	.12	10.8
Immature lesser grain borers:								
LGB_i-1	Wheat	12.6	38.6	3.6	4.2	.51	.12	10.8
Immature dermestids:[1]								
DM_l-1	Wheat	12.6	38.6	3.6	4.0	.49	.12	10.9
DM_l-1	Wheat	12.6	10.8	1.2	4.2	.37	.09	2.0

[1] Dermestids were *Trogoderma parabile* Beal.

TABLE 2.--Rice weevils, adults: Percentage of insects found live or dead after high frequency electrical treatment at 38.6 megacycles in wheat of 12.8 percent moisture

Experiment RW_a-1, September 26, 1956; mean of 10 replicates starting with 10 insects in each

Field intensity, initial sample temperature, and length of exposure	Temp. after treatment	One day after treatment				One week after treatment				Two weeks after treatment			
		Live		Dead		Live		Dead		Live		Dead	
		Normal	Injured	Mean	Range	Normal	Injured	Mean	Range	Normal	Injured	Mean	Range
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
1.2 kv./in.; 91°F.:													
5 seconds	94	74	21	5	0-20	68	9	23	0-40	73	4	23	0-40
13 seconds	102	57	25	18	0-60	38	8	54	33-90	41	5	54	33-90
21 seconds	109	17	43	40	7-70	25	2	73	54-100	23	3	74	56-100
29 seconds	116	0	34	66	36-100	5	7	88	70-100	6	6	88	70-100
37 seconds	120	1	14	85	60-100	5	3	92	67-100	5	2	93	73-100
45 seconds	128	1	0	99	90-100	0	0	100	--	0	0	100	--
53 seconds	132	0	0	100	--	0	0	100	--	0	0	100	--
2.4 kv./in.; 90°F.:													
1 second	92	31	43	26	0-45	19	21	60	8-86	23	16	61	40-86
3 seconds	98	3	38	59	33-89	3	7	90	78-100	3	6	91	80-100
5 seconds	106	7	33	60	20-90	2	4	94	70-100	1	4	95	78-100
7 seconds	112	2	10	88	70-100	0	3	97	70-100	0	2	98	80-100
9 seconds	120	2	7	91	80-100	0	1	99	91-100	0	0	100	--
11 seconds	125	0	0	100	--	0	0	100	--	0	0	100	--
3.6 kv./in.; 88°F.:													
1 second	95	2	80	18	0-33	1	6	93	70-100	1	6	93	70-100
2 seconds	102	4	34	62	20-89	0	0	100	--	0	0	100	--
3 seconds	110	0	9	91	72-100	0	0	100	--	0	0	100	--
4 seconds	118	0	0	100	--	0	0	100	--	0	0	100	--
5 seconds	125	0	0	100	--	0	0	100	--	0	0	100	--
4.7 kv./in.; 84°F.:													
.75 second	95	0	54	46	20-75	0	5	95	82-100	0	1	99	82-100
1.0 second	100	0	40	60	30-90	0	1	99	92-100	0	0	99	92-100
1.5 seconds	102	0	20	80	60-100	0	0	100	--	0	0	100	--
2.0 seconds	113	0	4	96	82-100	0	0	100	--	0	0	100	--
2.5 seconds	121	0	0	100	--	0	0	100	--	0	0	100	--
3.0 seconds	128	0	0	100	--	0	0	100	--	0	0	100	--
3.5 seconds	136	0	0	100	--	0	0	100	--	0	0	100	--
5.3 kv./in.; 92°F.:													
1.0 second	111	0	13	87	60-100	0	0	100	--	0	0	100	--
1.5 seconds	118	0	1	99	83-100	0	0	100	--	0	0	100	--
2.0 seconds	127	0	0	100	--	0	0	100	--	0	0	100	--
2.5 seconds	134	0	0	100	--	0	0	100	--	0	0	100	--
Checks.................	--	98	0	2	0-10	97	0	3	0-11	97	0	3	0-11

TABLE 3.--Rice weevils, adults: Percentage of insects found live or dead after high frequency electrical treatment at 38.8 megacycles in wheat of 11.4 percent moisture at initial temperature of 83° F.

Summary - Experiment RW_a-2, October 31, 1956; mean of 10 replicates starting with 10 insects in each

Field intensity and length of exposure	Temp. after treat-ment	One day after treatment				One week after treatment			
		Live		Dead		Live		Dead	
		Normal	Injured	Mean	Range	Normal	Injured	Mean	Range
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
1.2 kv./in.:									
5 seconds	88	75	23	2	0-10	67	12	21	0-50
13 seconds	96	47	40	13	0-30	55	18	27	0-60
21 seconds	104	21	59	20	0-40	23	17	60	10-90
30 seconds	114	13	37	50	22-90	12	7	81	44-100
40 seconds	119	2	17	81	60-100	3	4	93	70-100
50 seconds	125	0	6	94	70-100	0	4	96	70-100
60 seconds	133	1	0	99	91-100	0	0	100	--
2.4 kv./in.:									
1 second	88	7	92	1	0-10	13	24	63	50-80
3 seconds	96	1	80	19	0-40	1	11	88	60-100
5 seconds	104	2	51	47	30-88	2	0	98	89-100
7 seconds	110	0	23	77	50-100	0	0	100	--
9 seconds	118	0	3	97	80-100	0	0	100	--
11 seconds	124	0	2	98	90-100	0	0	100	--
3.6 kv./in.:									
.75 second	90	0	95	5	0-20	2	10	88	70-100
1.0 second	92	1	81	18	0-50	1	9	90	80-100
1.5 seconds	96	0	42	58	11-90	0	3	97	90-100
2.0 seconds	101	0	29	71	50-90	0	0	100	--
2.5 seconds	106	0	25	75	44-100	0	1	99	90-100
3.0 seconds	111	0	15	85	50-100	0	0	100	--
3.5 seconds	113	0	2	98	89-100	0	0	100	--
4.0 seconds	117	0	3	97	80-100	0	0	100	--
4.8 kv./in.:									
.75 second	94	0	82	18	0-40	0	2	98	80-100
1.0 second	99	0	73	27	10-50	0	2	98	90-100
1.5 seconds	107	0	22	78	44-90	0	0	100	--
2.0 seconds	115	0	5	95	80-100	0	0	100	--
2.5 seconds	124	0	1	99	90-100	0	0	100	--
3.0 seconds	130	0	0	100	--	0	0	100	--
5.4 kv./in.:									
.75 second	98	0	43	57	40-80	0	0	100	--
Checks...............	--	100	0	0	--	100	0	0	--

TABLE 4.--Rice weevils, adult: Percentage of insects found live or dead after high frequency electrical treatments in wheat of 13 percent moisture

Summary - Experiment RW_a-3, January 3, 1957; mean of 9 replicates starting with 10 insects in each

Frequency, field intensity, initial temperature of samples and length of exposure	Temp. after treatment	One day after treatment				One week after treatment			
		Live		Dead		Live		Dead	
		Normal	Injured	Mean	Range	Normal	Injured	Mean	Range
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
5 mc.									
3.5 kv./in.; 85° F.:									
6 seconds	91	3	96	1	0-10	1	47	52	33-78
12 seconds	99	1	84	15	0-50	0	11	89	70-100
18 seconds	106	0	67	33	10-60	0	4	96	80-100
24 seconds	115	0	27	73	10-90	0	1	99	90-100
30 seconds	119	0	10	90	80-100	0	0	100	--
38 seconds	129	0	3	97	80-100	0	0	100	--
46 seconds	138	0	0	100	--	0	0	100	--
10 mc.									
1.2 kv./in.; 90° F.:									
30 seconds	96	99	0	1	0-10	88	5	7	0-20
60 seconds	104	91	9	0	--	87	5	8	0-30
90 seconds	100	54	46	0	--	27	30	43	20-80
120 seconds	122	7	54	39	0-70	9	32	59	10-80
150 seconds	124	8	49	43	0-90	6	33	61	22-100
180 seconds	132	0	8	92	60-100	1	1	98	80-100
210 seconds	139	0	0	100	--	0	0	100	--
3.5 kv./in.; 89° F.:									
4 seconds	97	0	78	22	0-56	0	3	97	83-100
8 seconds	107	0	23	77	33-90	0	1	99	90-100
12 seconds	116	0	4	96	90-100	0	0	100	--
16 seconds	125	0	0	100	--	0	0	100	--
20 seconds	136	0	0	100	--	0	0	100	--
24 seconds	147	0	0	100	--	0	0	100	--
40 mc.									
3.5 kv./in.; 87° F.:									
1 second	94	0	92	8	0-20	0	8	92	30-100
2 seconds	101	0	57	43	0-70	0	1	99	90-100
3 seconds	109	0	24	76	40-100	0	1	99	90-100
4 seconds	117	0	2	98	90-100	0	0	100	--
Checks (room temperature)[1]	--	86	14	0	--	100	0	0	--
3.5 kv./in.; 102° F. for 16.5 hours before treatment:									
.75 second	105	0	50	33	0-90	0	6	94	80-100
1.5 seconds[2]	108	0	43	57	30-80	0	1	99	89-100
2.5 seconds	115	0	26	74	44-100	0	0	100	--
Checks (oven)................	--	63	34	2	0-10	74	2	24	10-33
3.5 kv./in.; 48° F. for 17.25 hours before treatment:									
4.5 seconds	95	0	47	53	30-80	0	12	89	70-100
6.0 seconds[2]	108	0	20	80	50-100	0	3	97	90-100
7.0 seconds	113	0	10	90	80-100	0	1	99	90-100
Checks......................	--	96	4	0	--	100	0	0	--

[1] 10 replicates.
[2] 8 replicates.

TABLE 5.--Rice weevils, adults: Percentage of insects found live or dead after high-frequency electrical treatments at 38.6 mc. and 3.5 kv./in. in wheat of 12.3 percent moisture, at various initial temperatures

Experiment RW$_a$-4, February 6, 1957; mean of 10 replicates starting with 10 insects in each

Pre-treatment conditioning and length of exposure	Temp. after treatment	One day after treatment				One week after treatment			
		Live		Dead		Live		Dead	
		Normal	Injured	Mean	Range	Normal	Injured	Mean	Range
	°F	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
47°F. for 17 hours:									
2.0 seconds	71	1	92	7	0-20	1	40	59	20-90
3.0 seconds	80	0	70	30	0-70	0	16	84	60-100
4.0 seconds	88	0	58	42	9-80	0	16	84	60-90
5.0 seconds	97	0	44	66	40-100	0	3	97	90-100
5.75 seconds	103	1	26	73	56-80	0	0	100	--
6.5 seconds	107	0	13	87	70-100	0	0	100	--
7.25 seconds	116	0	4	96	90-100	0	0	100	--
8.0 seconds	120	1	3	96	80-100	0	0	100	--
9.0 seconds	126	0	0	100	--	0	0	100	--
Checks................	--	97	0	3	0-20	96	0	4	0-20
60°F. for 20 hours:									
3.0 seconds	90	2	58	40	10-70	1	12	87	78-100
3.75 seconds	98	1	47	52	20-89	1	4	95	80-100
4.5 seconds	104	0	27	73	44-90	0	4	96	90-100
5.25 seconds	109	0	23	77	50-100	0	2	98	90-100
6.0 seconds	115	0	3	97	80-100	0	0	100	--
7.0 seconds	123	0	0	100	--	0	0	100	--
Checks................	--	97	1	2	0-10	95	1	4	0-10
86°F. for 23 hours:									
.75 second	92	0	100	0	--	0	20	80	60-90
1.5 seconds	99	0	59	41	30-70	0	1	99	90-100
2.25 seconds	106	0	48	52	10-80	0	0	100	--
3.0 seconds	111	0	14	86	80-100	0	1	99	90-100
3.75 seconds	117	0	1	99	90-100	0	0	100	--
4.5 seconds	122	0	0	100	--	0	0	100	--
Checks................	--	99	0	1	0-10	98	0	2	0-20
103°F. for 16 hours:									
.75 second	106	0	95	5	0-20	0	3	97	80-100
1.5 seconds	111	0	49	52	30-80	0	0	100	--
1.125 seconds	108	0	63	37	20-60	0	1	99	90-100
2.25 seconds	115	0	5	95	78-100	0	0	100	--
3.25 seconds	122	0	5	95	80-100	0	0	100	--
Checks................	--	96	1	30	0-20	91	0	9	0-30

TABLE 6.--Rice weevils, adult: Percentage killed in preconditioned samples raised to specified temperatures by high-frequency electrical treatments

Pre-treatment conditioning	95° F.	100° F.	105° F.	110° F.	115° F.	120° F.
	Percent	Percent	Percent	Percent	Percent	Percent
17 hours at 47° F.	60	70	81	89	95	98
20 hours at 60° F.	48	60	73	85	96	100
23 hours at 86° F.	13	36	60	82	96	100
16 hours at 103° F.	--	--	--	48	82	--

TABLE 7.--Rice weevils, adult: Percentage of insects found live or dead after high-frequency electrical treatments at 38.6 megacycles in wheat of 13.3 percent moisture and initial temperature of 83° F.

Experiment RW_a-5, March 6, 1957; mean of 10 replicates starting with 10 insects in each

Field intensity and length of exposure	Temperature after treatment	One day after treatment				One week after treatment			
		Live		Dead		Live		Dead	
		Normal	Injured	Mean	Range	Normal	Injured	Mean	Range
4.8 kv./in.	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
Sustained exposure:									
.3 second	90	0	95	5	0-20	0	15	85	70-100
.8 second	99	0	65	35	10-70	0	2	98	90-100
1.3 seconds	103	0	55	45	22-78	0	0	100	--
1.8 seconds	112	0	13	87	60-100	0	0	100	--
2.3 seconds	120	0	0	100	--	0	0	100	--
2.8 seconds	128	0	0	100	--	0	0	100	--
6.0 kv./in.									
Sustained exposure:									
.1 second	89	1	98	1	0-10	0	26	74	50-100
.4 second	96	0	72	28	0-50	0	1	99	90-100
.7 second	104	0	45	55	30-80	0	0	100	--
1.0 second	111	0	16	84	60-100	0	0	100	--
1.3 seconds	112	0	14	86	70-100	0	0	100	--
Pulsed exposure (0.2 second pulses-5 seconds between pulses)									
2 pulses-.4 second	97	0	77	23	10-60	0	0	100	--
4 pulses-.8 second	107	0	66	34	20-50	0	0	100	--
6 pulses-1.2 seconds	117	1	14	85	70-100	0	0	100	--
7.3 kv./in.									
Sustained exposure:									
.1 second	90	0	91	9	0-20	0	13	87	70-100
.3 second	96	0	67	33	10-90	0	0	100	--
.5 second	104	0	43	57	40-90	0	0	100	--
.7 second	110	0	23	77	50-100	0	1	99	90-100
Checks......................	--	99	0	1	0-10	96	0	4	0-10

TABLE 8.--Rice weevils, immature: Emergence of adults after high-frequency electrical treatments at 38.6 megacycles in wheat of 13.6 percent moisture and initial temperature of 86°F.

Summary-Experiment RW_i-1, November 28, 1956; mean of 10 replicates

Field intensity and length of exposure	Temperature after treatment	Emergence 3 weeks after treatment		Emergence 6 weeks after treatment		Total emergence for 3 and 6 weeks counts	
	°F.	Adults	Percentage of Check	Adults	Percentage of Check	Adults	Percentage of Check
1.2 kv./in.							
10 seconds	96	58	63	166	123	224	99
20 seconds	105	46	50	146	108	192	85
30 seconds	112	54	59	140	104	194	86
40 seconds	120	28	30	109	81	136	60
52 seconds	127	4	4	22	16	26	11
64 seconds	138	0	0	1	1	1	0
78 seconds	150	0	0	0	0	0	0
2.4 kv./in.							
2.5 seconds	98	78	85	112	83	190	84
5 seconds	107	79	85	119	89	198	87
8 seconds	117	26	28	147	109	173	76
11 seconds	127	2	2	15	12	18	8
14 seconds	138	0	0	1	0	1	0
17 seconds	149	0	0	0	0	0	0
20 seconds	158	0	0	0	0	0	0
3.6 kv./in.							
1 second	97	78	85	138	102	216	96
2 seconds	105	82	89	141	103.	222	98
3 seconds	115	71	77	133	99	204	90
4 seconds	123	19	21	54	40	73	31
5 seconds	127	5	5	22	16	26	12
6 seconds	137	0	0	1	1	1	1
7 seconds	141	0	0	0	0	0	0
8 seconds	153	0	0	0	0	0	0
9 seconds	152	0	0	0	0	0	0
4.8 kv./in.							
.75 second	99	63	68	154	115	218	96
1.5 seconds	111	59	64	149	111	207	91
2.25 seconds	122	11	12	39	29	50	22
3 seconds	130	0	0	3	3	4	2
3.75 seconds	143	0	0	0	1	0	0
4.5 seconds	152	0	0	0	0	0	0
Checks....................	--	93	100	134	100	227	100

TABLE 9.--Rice weevils, immature: Emergence of adults after high-frequency electrical treatment at 38.6 megacycles and 3.6 kv./in. on different age groups in wheat of 12.6 to 13.2 percent moisture

Summary - Experiment RW$_i$-2, April 9, 1957; mean of 10 replicates

Age group, degree of infestation as determined by X-ray, and length of exposure	Temp. after treatment	Emergence at indicated period after treatment										Total emergence	
		3 weeks		4 weeks		5 weeks		6 weeks		7 weeks			
		Normal	Injured	Normal	Injured	Normal	Injured	Normal	Injured	Normal	Injured		
	°F.	No.	No.	No.	No.	No.	No.	No.	No.	No.	No.	No.	Pct. of check
A (eggs - .5 to 4 days):													
.75 second	89	0	0	0	0	29.8	--	19.1	--	1.4	--	50.3	102.0
1.5 seconds	98	0	0	0	0	26.8	--	24.8	--	1.1	--	52.7	107.1
3 seconds	110	0	0	0.1	0	22.0	--	18.9	--	2.5	--	43.5	88.4
4.5 seconds	126	0	0	0	0	0.9	--	1.7	--	0.7	--	3.3	6.8
6 seconds	137	0	0	0	0	1.0	--	0	--	0	--	0.1	0.2
7.5 seconds	148	0	0	0	0	0	--	0	--	0	--	0	0
9 seconds	156	0	0	0	0	0	--	0	--	0	--	0	0
Checks..................	--	0	0	0	0	24.8	--	22.1	--	2.3	--	49.2	100
B (eggs and larvae - 5 to 12 days) 17.0 percent infested:		2 weeks		3 weeks		4 weeks		5 weeks		6 weeks			
.75 second	92	0	0	7	0	70.9	0	34.1	--	2.6	--	108.3	108.6
1.5 seconds	98	0	0	1.1	0	58.1	0	42.1	--	1.7	--	103.0	103.3
3 seconds	113	0	0	2	0	34.2	0	58.6	--	4.4	--	97.4	97.7
4.5 seconds	126	0	0	0	0	2.9	0	9.4	--	1.3	--	13.6	13.6
6 seconds	138	0	0	0	0	0	0	0	--	0	--	0	0
7.5 seconds	149	0	0	0	0	0	0	0	--	0	--	0	0
9 seconds	164	0	0	0	0	0	0	0	--	0	--	0	0
Checks..................	--	0	0	1	0	45.0	0	51.5	--	32.2	--	99.7	100
C (larvae - 12 to 19 days) 21.5 percent infested:		1 week		2 weeks		3 weeks		4 weeks		5 weeks			
.75 second	94	0	0	0.8	0	62.2	0	35.5	0	--	--	98.5	99.3
1.5 seconds	100	0.3	0	.4	0	64.2	0	29.5	0	--	--	94.4	95.2
3 seconds	115	0	0	2	0	48.3	0	39.6	0	--	--	88.1	88.8
4.5 seconds	128	0	0	0	0	1.9	0	3.7	0	.3	--	5.9	5.9
6 seconds	139	0	0	0	0	0	0	0.1	0	.1	--	.2	.2
7.5 seconds	148	0	0	0	0	0	0	0	0	0	--	0	0
9 seconds	161	0	0	0	0	0	0	0	0	0	--	0	0
Checks..................	--	0	0	.6	0	78.1	0	20.3	0	.2	--	99.2	100
D (older larvae and few pupae - 19 to 26 days) 17.5 percent infested:													
.75 second	96	.4	0	58.7	0	32.1	0	--	--	--	--	91.2	99.5
1.5 seconds	102	.6	.3	65.3	.1	26.3	0	--	--	--	--	92.6	101.0
3 seconds	114	.1	0	51.6	.5	32.0	0	--	--	--	--	84.2	91.8
4.5 seconds	129	0	0	4.9	0	3.1	0	--	--	--	--	8.0	8.7
6 seconds	139	0	0	.3	0	.1	0	0	0	--	--	.4	.4
7.5 seconds	150	0	0	0	0	0	0	0	0	--	--	0	0
9 seconds	164	0	0	0	0	0	0	0	0	--	--	0	0
Checks..................	--	.6	0	73.4	.1	16.2	1.4	--	--	--	--	91.7	100
E (pupae and few older larvae - 26 to 33 days) 11.0 percent infested:													
.75 second	94	33.0	5.0	34.6	1.5	1.1	.2	--	--	--	--	75.4	87.4
1.5 seconds	100	34.3	7.2	36.9	1.7	1.5	.2	--	--	--	--	81.8	94.8
3 seconds	114	27.1	3.3	40.8	.3	1.1	0	--	--	--	--	72.6	84.1
4.5 seconds	125	3.0	.4	9.0	.2	.3	0	--	--	--	--	12.9	14.9
6 seconds	138	0	0	.3	0	0	0	--	--	--	--	.3	.4
7.5 seconds	151	0	0	0	0	0	0	--	--	--	--	0	0
9 seconds	162	0	0	0	0	0	0	--	--	--	--	0	0
Checks..................	--	43.6	0	41.4	0	1.3	0	--	--	--	--	86.3	100

TABLE 10.--Rice weevils, immature: Percentage of total emergence 5 weeks after high-frequency electrical treatment compared to no treatment

Stage of insect when treated	Treated	Checks
	Percent	Percent
Egg..................................	47	50
Young larvae.........................	44	45
Middle aged larvae...................	55	79
Older larvae.........................	65	80
Pupae and pre-emergence adults........	42	51
Average..............................	51	61

TABLE 11.--Confused flour beetle adults: Percentage of insects found live or dead after high frequency electrical treatment at 38.6 megacycles in wheat of 13.3 percent moisture

Summary - Experiment CFB$_a$-1, March 5, 1957; mean of 10 replications, starting with 10 insects in each

Field intensity, initial temperature of samples, and length of exposure	Temperature after treatment	Two days after treatment			One week after treatment		
		Live		Dead	Live		Dead
		Normal	Injured		Normal	Injured	
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
3.6 kv./in.; 84° F.:							
.5 second	85	0	100	0	0	98	2
1 second	90	0	74	26	0	67	33
2 seconds	98	0	42	58	0	28	72
3 seconds	106	0	16	84	0	14	86
4 seconds	116	0	2	98	0	0	100
5 seconds	123	0	1	99	0	0	100
4.8 kv./in.; 84° F.:							
.3 second	86	0	100	0	0	100	0
.8 second	97	0	36	64	0	31	69
1.3 seconds	100	0	36	64	0	33	67
1.8 seconds	107	0	34	66	0	22	78
2.3 seconds	116	0	2	98	0	2	98
5.9 kv./in.; 83° F.:							
.1 second	86	0	97	3	10	85	5
.4 second	92	0	66	34	0	59	41
.7 second	100	0	25	75	0	21	79
1 second	108	0	10	90	0	10	90
1.3 seconds	109	0	18	82	0	14	86
6.8 kv./in.; 81° F.:							
.1 second	86	0	80	20	0	72	28
.4 second	97	0	44	56	0	36	64
.7 second	107	0	18	82	0	9	91
Checks...................	--	100	0	0	100	0	0

TABLE 12.--Confused flour beetle adults: Percentage of insects found live or dead after high-frequency electrical treatment at 38.6 megacycles in wheat shorts of 13.0 percent moisture at initial temperature of 84° F.

Summary - Experiment CFB$_a$ - 2, May 7, 1957; mean of 10 replicates starting with 10 insects in each

Field intensity and length of exposure	Temperature after treatment	One day after treatment			One week after treatment			Three weeks after treatment		
		Live		Dead	Live		Dead	Live		Dead
		Normal	Injured		Normal	Injured		Normal	Injured	
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
3.6 kv./in.:										
.5 second	88	55	45	0	68	32	0	80	20	0
1 second	93	6	90	4	8	88	4	60	36	4
2 seconds	102	1	79	20	0	80	20	10	63	27
3 seconds	111	3	78	19	4	76	20	5	65	30
4 seconds	121	3	50	47	1	44	55	0	39	61
5 seconds	131	0	30	70	0	15	85	1	10	89
6 seconds	140	0	18	82	0	8	92	2	5	93
7.2 kv./in.:										
.2 second	93	8	82	10	0	87	13	13	69	18
.5 second	105	0	69	31	19	44	37	0	49	51
.8 second	114	0	72	28	0	67	33	6	31	63
1 second	125	0	55	45	0	47	53	0	19	81
1.2 seconds	127	0	50	50	0	44	56	0	13	87
1.4 seconds	134	4	12	84	1	17	82	0	6	94
1.6 seconds	146	0	1	99	0	0	100	0	0	100
Checks.............	--	100	0	0	100	0	0	100	0	0

TABLE 13.--Confused flour beetle larvae: Percentage of insects found live or dead after high-frequency electrical treatment at 38.6 megacycles and 3.6 kv./in. in wheat shorts of 13.0 percent moisture at initial temperature of 81° F.

Summary--Experiment CFB$_i$-1, May 8, 1957; mean of 10 replicates starting with 10 insects in each

Length of exposure	Temperature after treatment	1 week after treatment							3 weeks after treatment						
		Larvae		Pupae		Adult		All stages	Larvae		Pupae		Adult		All stages
		Live	Dead	Live	Dead	Live	Dead	Dead	Live	Dead	Live	Dead	Live	Dead	Dead
	°F.	Pct	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
.5 second	87	14	9	77	0	0	0	9	0	5	0	1	94	0	6
1 second	91	9	16	75	0	0	0	16	0	18	0	0	82	0	18
2 seconds	101	10	23	67	0	0	0	23	0	27	0	0	70	3	30
3 seconds	111	19	24	57	0	0	0	24	0	27	0	0	72	1	28
4 seconds	119	9	46	45	0	0	0	46	0	40	0	12	47	1	33
5 seconds	129	1	75	24	0	0	0	75	0	45	0	31	24	0	76
6 seconds	137	2	91	7	0	0	0	92	0	91	0	0	9	0	91
Checks..........	--	24	0	76	0	0	0	0	0	0	0	2	98	0	2

TABLE 14.--Red flour beetles, adults: Percentage of insects found live or dead after high-frequency electrical treatment at 38.6 megacycles and 3.6 kv./in. in wheat shorts at 13.0 percent moisture at initial temperature of 81° F.

Summary--Experiment RFB_a-1, May 8, 1957; mean of 10 replicates starting with 10 insects in each

Length of exposure	Temperature after treatment	One day after treatment			One week after treatment			Three weeks after treatment		
		Live		Dead	Live		Dead	Live		Dead
		Normal	Injured		Normal	Injured		Normal	Injured	
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
.5 second	86	84	9	7	74	24	2	91	4	5
1 second	90	29	67	4	20	67	13	71	11	18
2 seconds	100	2	66	32	5	62	33	39	18	43
3 seconds	110	1	46	53	0	43	57	8	29	63
4 seconds	118	0	19	82	0	4	96	0	1	99
5 seconds	128	0	1	99	0	2	98	0	2	98
6 seconds	136	0	0	100	0	0	100	0	0	100
Checks..............	--	100	0	0	100	0	0	100	0	0

TABLE 15.--Granary weevils, adults: Percentage of insects found live or dead after high-frequency electrical treatment at 39 megacycles and 3.3 kv./in. in wheat of 12.7 percent moisture and initial temperature of 86° F.

Summary--Experiment GW_a-1, June 12, 1957; mean of 10 replicates starting with 10 insects in each

Length of exposure	Temperature after treatment	One day after treatment			One week after treatment			Two weeks after treatment		
		Live		Dead	Live		Dead	Live		Dead
		Normal	Injured		Normal	Injured		Normal	Injured	
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
.5 second	91	12	75	13	0	30	70	0	26	74
1 second	94	1	85	14	0	15	85	0	12	88
2 seconds	103	0	73	27	0	9	91	0	7	93
3 seconds	113	0	40	60	0	1	99	0	0	100
4 seconds	122	0	22	78	0	0	100	0	0	100
5 seconds	128	0	1	99	0	0	100	0	0	100
6 seconds	135	0	2	98	0	0	100	0	0	100
Checks..............	--	99	0	1	96	0	4	93	0	6

TABLE 16.--Lesser grain borers, adults: Percentage of insects found live or dead after high-frequency electrical treatment at 39 megacycles and 3.6 kv./in. in wheat of 12.7 percent moisture and initial temperature of 84° F.

Summary--Experiment LGB_a-1, June 12, 1957; mean of 10 replicates starting with 10 insects in each

Length of exposure	Temperature after treatment	One day after treatment			One week after treatment			Two weeks after treatment		
		Live		Dead	Live		Dead	Live		Dead
		Normal	Injured		Normal	Injured		Normal	Injured	
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
.5 second	88	93	0	7	83	0	17	75	0	25
1 second	92	93	0	7	71	0	29	65	0	35
2 seconds	101	68	0	32	53	0	47	36	0	64
3 seconds	111	46	0	54	36	0	67	23	0	77
4 seconds	120	37	0	63	25	0	75	14	0	86
5 seconds	129	6	0	94	3	0	97	1	0	99
6 seconds	137	3	0	97	2	0	98	1	0	99
Checks..............	89	94	0	6	89	0	11	76	0	24

TABLE 17.--Lesser grain borers, immatures: Emergence of adults after high frequency electrical treatment at 39 megacycles and 3.6 kv./in. on different age groups in wheat of 12.5 to 12.7 percent moisture

Summary - Experiment LGB$_1$-1, June 11, 1957; mean of 10 replicates

Age group, degree of infestation, and length of exposure	Temp. after treatment	Live	Dead	Total		Live	Dead	Total		Live	Dead	Total		Total emergence	
		Count	Count	Count	Percentage of check	Count	Count	Count	Percentage of check	Count	Count	Count	Percentage of check	Count	Percentage of check
		38 days				45 days				50 days					
A (0-5 days) 2.4 percent infested:	°F.	Avg.	Avg.	Avg.	Pct.	Avg.	Avg.	Avg.	Pct.	Avg.	Avg.	Avg.	Pct.	Avg.	Pct.
1 second	95	7.1	0	7.1	94.7	6.1	0	6.1	88.4	5.1	0	5.1	318.8	18.3	114.4
2 seconds	105	7.7	0.1	7.8	104.0	9.0	.1	9.1	131.9	5.9	0	5.9	368.8	22.8	142.5
3 seconds	115	7.8	.1	7.9	105.3	7.0	0	7.0	101.4	1.7	0	1.7	106.3	16.6	103.8
4 seconds	124	3.8	0	3.8	50.1	2.5	0	2.5	36.2	1.2	0	1.2	75.0	7.5	46.9
5 seconds	130	.9	0	.9	12.0	1.0	0	1.0	14.5	.3	0	.3	18.8	2.2	13.8
6 seconds	140	.1	0	.1	1.3	.1	0	.1	1.5	0	0	0	0	.2	1.3
7 seconds	146	.1	0	.1	1.3	0	0	0	0	0	0	0	0	.1	.6
Checks........................	--	7.4	.1	7.5	100.0	6.9	0	6.9	100.0	1.6	0	1.6	100.0	16.0	100.0
B (5 days-2 weeks) 12.6 percent infested:		33 days				40 days				47 days					
1 second	93	41.1	0	41.1	99.8	33.4	0	33.4	119.7	23.3	0.2	23.5	88.6	98.0	102.5
2 seconds	101	44.8	0	44.8	108.8	30.8	0	30.8	110.4	27.8	0	27.8	104.9	103.4	108.2
3 seconds	111	46.5	0	46.5	112.9	25.4	0	25.4	91.0	23.7	0	23.7	89.4	95.6	100.0
4 seconds	120	32.2	.1	32.3	78.4	23.7	0	23.7	84.9	20.9	0	20.9	78.9	76.9	80.4
5 seconds	128	10.1	0	10.1	24.5	10.3	0	10.3	36.9	5.5	0	5.5	20.8	25.9	27.1
6 seconds	136	2.1	0	2.1	5.1	2.6	0	2.6	9.3	2.0	0	2.0	7.5	6.7	7.0
7 seconds	146	0.2	0	.2	.5	1.0	0	1.0	3.6	.3	0	.3	1.1	1.5	1.7
Checks........................	--	41.2	0	41.2	100.0	27.9	0	27.9	100.0	26.5	0	26.5	100.0	95.6	100.0
C (2-3 weeks) 8.4 percent infested:		20 days				27 days				34 days					
1 second	93	23.8	0	23.8	102.6	20.0	0	20.2	92.6	15.4	0	15.4	75.9	59.2	90.9
2 seconds	102	22.7	0	22.7	97.8	23.2	0	23.2	107.4	14.7	0	14.7	72.4	60.6	93.1
3 seconds	113	23.1	.1	23.2	100.0	25.0	0	25.0	115.7	13.6	0	13.6	67.0	61.8	94.9
4 seconds	122	16.1	.3	16.4	70.7	22.1	.1	22.2	102.8	13.8	.1	13.9	68.5	52.5	80.6
5 seconds	130	3.6	.2	3.8	16.4	8.2	0	8.2	38.0	4.1	0	4.1	20.2	16.1	24.7
6 seconds	137	.8	0	.8	3.4	1.1	0	1.1	5.1	1.0	0	1.0	4.9	2.9	4.5
7 seconds	143	.3	.2	.5	2.2	.5	.2	.7	3.2	.2	0	.2	1.0	1.4	2.2
Checks........................	--	22.8	.4	23.2	100.0	21.6	0	21.6	100.0	20.3	0	20.3	100.0	65.1	100.0
D (3-4 1/2 weeks) 1.4 percent infested:		16 days				23 days				30 days					
1 second	92	4.0	0	4.0	148.1	6.1	0	6.1	105.2	1.0	0	1.0	37.0	11.1	99.1
2 seconds	101	4.3	0	4.3	159.3	4.5	0	4.5	77.6	1.6	0	1.6	59.3	10.4	92.9
3 seconds	110	2.7	0	2.7	100.0	4.5	0	4.5	77.6	2.4	0	2.4	88.9	9.6	85.7
4 seconds	120	3.4	0	3.4	125.9	4.1	0	4.1	70.7	1.2	0	1.2	44.4	8.7	77.7
5 seconds	129	.7	0	.7	25.9	1.7	0	1.7	29.3	1.1	0	1.1	40.7	3.5	31.3
6 seconds	137	0	0	0	0	.3	0	.3	5.2	.4	0	.4	14.8	.7	6.3
7 seconds	145	0	0	0	0	0	0	0	0	.1	0	.1	3.7	.1	.9
Checks........................	--	2.7	0	2.7	100.0	5.8	0	5.8	100.0	2.7	0	2.7	100.0	11.2	100.0

TABLE 18.--Dermestids, immatures: Percentage of insects found dead after high-frequency electrical treatments in wheat of 12.6 percent moisture

Summary - Experiment Dm_1-1, 6/11/58; Mean of 10 replicates, starting with 10 insects in each

Treatment and length of exposure	Temperature after Treatment	Mortality after--					
		2 Days	1 week	2 weeks	3 weeks	4 weeks	5 weeks
	°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
38.6 megacycles							
Field intensity 3.6 kv/in.							
1 second	90.8	6.3	10.4	17.7	23.2	23.4	23.4
2 seconds	99.9	21.5	29.0	33.3	36.8	37.1	37.5
3 seconds	109.0	42.4	52.5	55.6	59.6	60.2	62.6
4 seconds	117.3	60.0	70.0	72.0	77.0	80.0	80.0
5 seconds	127.2	72.4	78.6	84.7	86.7	86.7	86.7
6 seconds	134.1	95.0	96.0	97.0	97.0	98.0	99.0
7 seconds	143.4	89.0	95.0	98.0	98.0	99.0	99.0
8 seconds	152.1	85.7	92.9	96.0	99.0	100.0	100.0
9 seconds	158.7	94.9	99.0	100.0	100.0	100.0	100.0
10 seconds	165.4	96.2	99.1	100.0	100.0	100.0	100.0
Field intensity 1.2 kv/in.							
8 seconds	89.4	4.1	8.3	8.3	8.3	8.3	8.3
16 seconds	101.3	9.1	16.2	18.2	20.2	22.2	23.3
24 seconds	109.0	24.8	28.7	31.7	33.7	34.3	34.3
32 seconds	116.1	45.6	53.5	53.5	53.5	55.4	55.4
40 seconds	122.9	43.3	60.6	63.6	64.7	65.7	68.0
48 seconds	132.9	56.5	72.0	75.7	76.8	78.8	78.8
56 seconds	139.0	71.7	89.9	92.9	94.0	95.0	95.0
64 seconds	147.1	40.4	86.9	99.0	97.0	97.0	97.0
74 seconds	157.8	38.0	85.0	99.0	99.0	99.0	99.0
10.8 megacycles							
Field intensity 3.6 kv/in.							
2 seconds	92.7	0	1.0	1.0	1.0	2.0	2.0
5 seconds	102.0	13.0	14.2	15.1	16.8	18.1	19.4
8 seconds	109.7	14.9	17.0	20.0	20.0	20.0	20.0
11 seconds	119.7	31.0	30.0	32.0	34.0	35.0	36.0
14 seconds	125.8	25.5	32.7	36.0	43.0	44.0	44.4
17 seconds	135.2	64.6	70.4	71.4	64.3	74.8	75.5
20 seconds	139.8	55.4	75.2	78.2	79.2	79.2	78.1
24 seconds	157.7	75.7	91.9	91.9	93.7	93.9	93.9
28 seconds	169.2	88.9	99.0	99.0	99.0	99.0	99.0
Checks.......................	--	3.3	6.1	7.5	18.4	18.4	18.4

TABLE 19.--Lethal temperatures in grain or treatment media for indicated mortalities of stored-grain insects at indicated periods following high-frequency electrical treatment. (See footnote explanations at end of table)

<table>
<tr><th rowspan="2">Experiment and treatment</th><th colspan="6">50 percent mortality</th><th colspan="6">80 percent mortality</th><th colspan="6">90 percent mortality</th><th colspan="6">100 percent mortality[1]</th></tr>
<tr><th colspan="3">1 day</th><th colspan="3">1 week</th><th colspan="3">1 day</th><th colspan="3">1 week</th><th colspan="3">1 day</th><th colspan="3">1 week</th><th colspan="3">1 day</th><th colspan="3">1 week</th></tr>
<tr><td></td><td colspan="3">°F.</td><td colspan="3">°F.</td><td colspan="3">°F.</td><td colspan="3">°F.</td><td colspan="3">°F.</td><td colspan="3">°F.</td><td colspan="3">°F.</td><td colspan="3">°F.</td></tr>
<tr><td>RW_a-1</td><td colspan="24"></td></tr>
<tr><td>1.2 kv./in.</td><td colspan="3">112</td><td colspan="3">101</td><td colspan="3">119</td><td colspan="3">113</td><td colspan="3">122</td><td colspan="3">118</td><td colspan="3">133</td><td colspan="3">128</td></tr>
<tr><td>2.4 kv./in.</td><td colspan="3">98</td><td colspan="3">(92)</td><td colspan="3">111</td><td colspan="3">95</td><td colspan="3">117</td><td colspan="3">98</td><td colspan="3">125</td><td colspan="3">125</td></tr>
<tr><td>3.6 kv./in.</td><td colspan="3">101</td><td colspan="3">(90)</td><td colspan="3">106</td><td colspan="3">(93)</td><td colspan="3">110</td><td colspan="3">(95)</td><td colspan="3">118</td><td colspan="3">102</td></tr>
<tr><td>4.7 kv./in.</td><td colspan="3">97</td><td colspan="3">(87)</td><td colspan="3">102</td><td colspan="3">(92)</td><td colspan="3">108</td><td colspan="3">(94)</td><td colspan="3">122</td><td colspan="3">102</td></tr>
<tr><td>RW_a-2</td><td colspan="24"></td></tr>
<tr><td>1.2 kv./in.</td><td colspan="3">114</td><td colspan="3">101</td><td colspan="3">119</td><td colspan="3">113</td><td colspan="3">123</td><td colspan="3">118</td><td colspan="3">---</td><td colspan="3">133</td></tr>
<tr><td>2.4 kv./in.</td><td colspan="3">104</td><td colspan="3">(86)</td><td colspan="3">111</td><td colspan="3">93</td><td colspan="3">114</td><td colspan="3">97</td><td colspan="3">---</td><td colspan="3">110</td></tr>
<tr><td>3.6 kv./in.</td><td colspan="3">96</td><td colspan="3">(85)</td><td colspan="3">106</td><td colspan="3">(88)</td><td colspan="3">112</td><td colspan="3">92</td><td colspan="3">---</td><td colspan="3">101</td></tr>
<tr><td>4.8 kv./in.</td><td colspan="3">103</td><td colspan="3">(86)</td><td colspan="3">107</td><td colspan="3">(89)</td><td colspan="3">112</td><td colspan="3">92</td><td colspan="3">130</td><td colspan="3">107</td></tr>
<tr><td></td><td colspan="3">1 day</td><td colspan="3">11 days</td><td colspan="3">1 day</td><td colspan="3">11 days</td><td colspan="3">1 day</td><td colspan="3">11 days</td><td colspan="3">1 day</td><td colspan="3">11 days</td></tr>
<tr><td>RW_a-3</td><td colspan="24"></td></tr>
<tr><td>3.5 kv./in.</td><td colspan="24"></td></tr>
<tr><td>5 mc.</td><td colspan="3">110</td><td colspan="3">(91)</td><td colspan="3">117</td><td colspan="3">97</td><td colspan="3">119</td><td colspan="3">99</td><td colspan="3">138</td><td colspan="3">119</td></tr>
<tr><td>10 mc.</td><td colspan="3">103</td><td colspan="3">(93)</td><td colspan="3">108</td><td colspan="3">(96)</td><td colspan="3">112</td><td colspan="3">(96)</td><td colspan="3">125</td><td colspan="3">116</td></tr>
<tr><td>40 mc.</td><td colspan="3">102</td><td colspan="3">(91)</td><td colspan="3">111</td><td colspan="3">(93)</td><td colspan="3">115</td><td colspan="3">(94)</td><td colspan="3">---</td><td colspan="3">117</td></tr>
<tr><td>1.2 kv./in.</td><td colspan="24"></td></tr>
<tr><td>10 mc.</td><td colspan="3">125</td><td colspan="3">116</td><td colspan="3">129</td><td colspan="3">125</td><td colspan="3">132</td><td colspan="3">128</td><td colspan="3">139</td><td colspan="3">139</td></tr>
<tr><td></td><td colspan="3">1 day</td><td colspan="3">1 week</td><td colspan="3">1 day</td><td colspan="3">1 week</td><td colspan="3">1 day</td><td colspan="3">1 week</td><td colspan="3">1 day</td><td colspan="3">1 week</td></tr>
<tr><td>RW_a-4</td><td colspan="24"></td></tr>
<tr><td>3.5 kv./in.</td><td colspan="24"></td></tr>
<tr><td>47° F.</td><td colspan="3">91</td><td colspan="3">(67)</td><td colspan="3">105</td><td colspan="3">82</td><td colspan="3">111</td><td colspan="3">90</td><td colspan="3">126</td><td colspan="3">103</td></tr>
<tr><td>60° F.</td><td colspan="3">96</td><td colspan="3">(73)</td><td colspan="3">108</td><td colspan="3">(86)</td><td colspan="3">112</td><td colspan="3">93</td><td colspan="3">122</td><td colspan="3">115</td></tr>
<tr><td>86° F.</td><td colspan="3">103</td><td colspan="3">(88)</td><td colspan="3">109</td><td colspan="3">92</td><td colspan="3">112</td><td colspan="3">95</td><td colspan="3">122</td><td colspan="3">106</td></tr>
<tr><td>103° F.</td><td colspan="3">111</td><td colspan="3">(103)</td><td colspan="3">115</td><td colspan="3">(105)</td><td colspan="3">117</td><td colspan="3">(105)</td><td colspan="3">---</td><td colspan="3">111</td></tr>
<tr><td>RW_a-5</td><td colspan="24"></td></tr>
<tr><td>4.8 kv./in.</td><td colspan="3">103</td><td colspan="3">(87)</td><td colspan="3">110</td><td colspan="3">90</td><td colspan="3">113</td><td colspan="3">92</td><td colspan="3">120</td><td colspan="3">104</td></tr>
<tr><td>6.0 kv./in.</td><td colspan="3">102</td><td colspan="3">(87)</td><td colspan="3">110</td><td colspan="3">(89)</td><td colspan="3">---</td><td colspan="3">92</td><td colspan="3">---</td><td colspan="3">103</td></tr>
<tr><td>6.0 kv./in. (intermittant)</td><td colspan="3">107</td><td colspan="3">(89)</td><td colspan="3">115</td><td colspan="3">(94)</td><td colspan="3">---</td><td colspan="3">(96)</td><td colspan="3">---</td><td colspan="3">97</td></tr>
<tr><td>7.3 kv./in.</td><td colspan="3">102</td><td colspan="3">(86)</td><td colspan="3">108</td><td colspan="3">(88)</td><td colspan="3">---</td><td colspan="3">(89)</td><td colspan="3">---</td><td colspan="3">96</td></tr>
<tr><td></td><td colspan="3">2 days</td><td colspan="3">2 weeks</td><td colspan="3">2 days</td><td colspan="3">2 weeks</td><td colspan="3">2 days</td><td colspan="3">2 weeks</td><td colspan="3">2 days</td><td colspan="3">2 weeks</td></tr>
<tr><td>DM_i-1</td><td colspan="24"></td></tr>
<tr><td>3.6 kv./in.</td><td colspan="24"></td></tr>
<tr><td>10.8 mc.</td><td colspan="3">132</td><td colspan="3">129</td><td colspan="3">158</td><td colspan="3">142</td><td colspan="3">---</td><td colspan="3">155</td><td colspan="3">---</td><td colspan="3">---</td></tr>
<tr><td>38.6 mc.</td><td colspan="3">112</td><td colspan="3">107</td><td colspan="3">132</td><td colspan="3">122</td><td colspan="3">146</td><td colspan="3">130</td><td colspan="3">---</td><td colspan="3">159</td></tr>
<tr><td>1.2 kv./in.</td><td colspan="24"></td></tr>
<tr><td>38.6 mc.</td><td colspan="3">---</td><td colspan="3">117</td><td colspan="3">---</td><td colspan="3">132</td><td colspan="3">---</td><td colspan="3">140</td><td colspan="3">---</td><td colspan="3">---</td></tr>
<tr><td></td><td colspan="3">2 days</td><td colspan="3">1 week</td><td colspan="3">2 days</td><td colspan="3">1 week</td><td colspan="3">2 days</td><td colspan="3">1 week</td><td colspan="3">2 days</td><td colspan="3">1 week</td></tr>
<tr><td>CFB_a-1</td><td colspan="24"></td></tr>
<tr><td>3.6 kv./in.</td><td colspan="3">96</td><td colspan="3">93</td><td colspan="3">104</td><td colspan="3">102</td><td colspan="3">109</td><td colspan="3">108</td><td colspan="3">---</td><td colspan="3">116</td></tr>
<tr><td>4.8 kv./in.</td><td colspan="3">97</td><td colspan="3">96</td><td colspan="3">106</td><td colspan="3">106</td><td colspan="3">112</td><td colspan="3">112</td><td colspan="3">---</td><td colspan="3">---</td></tr>
<tr><td>5.9 kv./in.</td><td colspan="3">95</td><td colspan="3">93</td><td colspan="3">102</td><td colspan="3">101</td><td colspan="3">---</td><td colspan="3">---</td><td colspan="3">---</td><td colspan="3">---</td></tr>
<tr><td>5.8 kv./in.</td><td colspan="3">95</td><td colspan="3">93</td><td colspan="3">106</td><td colspan="3">103</td><td colspan="3">---</td><td colspan="3">107</td><td colspan="3">---</td><td colspan="3">---</td></tr>
<tr><td></td><td colspan="2">2 da</td><td colspan="2">1 wk</td><td colspan="2">3 wk</td><td colspan="2">2 da</td><td colspan="2">1 wk</td><td colspan="2">3 wk</td><td colspan="2">2 da</td><td colspan="2">1 wk</td><td colspan="2">3 wk</td><td colspan="2">2 da</td><td colspan="2">1 wk</td><td colspan="2">3 wk</td></tr>
<tr><td>CFB_a-2</td><td colspan="24"></td></tr>
<tr><td>3.6 kv./in.</td><td colspan="2">123</td><td colspan="2">119</td><td colspan="2">116</td><td colspan="2">137</td><td colspan="2">129</td><td colspan="2">127</td><td colspan="2">---</td><td colspan="2">138</td><td colspan="2">132</td><td colspan="2">---</td><td colspan="2">---</td><td colspan="2">---</td></tr>
<tr><td>7.2 kv./in.</td><td colspan="2">123</td><td colspan="2">120</td><td colspan="2">106</td><td colspan="2">138</td><td colspan="2">137</td><td colspan="2">123</td><td colspan="2">143</td><td colspan="2">142</td><td colspan="2">130</td><td colspan="2">146</td><td colspan="2">146</td><td colspan="2">146</td></tr>
<tr><td></td><td colspan="3">1 week</td><td colspan="3">3 weeks</td><td colspan="3">1 week</td><td colspan="3">3 weeks</td><td colspan="3">1 week</td><td colspan="3">3 weeks</td><td colspan="3">1 week</td><td colspan="3">3 weeks</td></tr>
<tr><td>CFB_1-1</td><td colspan="24"></td></tr>
<tr><td>3.6 kv./in.</td><td colspan="3">120</td><td colspan="3">117</td><td colspan="3">132</td><td colspan="3">132</td><td colspan="3">137</td><td colspan="3">137</td><td colspan="3">---</td><td colspan="3">---</td></tr>
</table>

See footnotes at end of table.

TABLE 19.--Lethal temperatures in grain or treatment media for indicated mortalities of stored-grain insects at indicated periods following high-frequency electrical treatment. (See footnote explanations at end of table)--Continued

Experiment and treatment	50 percent mortality			80 percent mortality			90 percent mortality			100 percent mortality[1]		
	1 da	1 wk	3 wk	1 da	1 wk	3 wk	1 da	1 wk	3 wk	1 da	1 wk	3 wk
	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.
RFB$_a$-1												
3.6 kv./in.	108	107	104	118	116	113	123	117	116	136	136	136
	1 da	1 wk	2 wk	1 da	1 wk	2 wk	1 da	1 wk	2 wk	1 da	1 wk	2 wk
GW$_a$-1												
3.3 kv./in.	111	(88)	(88)	122	93	92	125	100	98	---	122	113
LGB$_a$-1	112	105	97	124	120	114	127	126	122	---	---	---
	6 weeks			6 weeks			6 weeks			6 weeks		
RW$_i$-1												
1.2 kv./in.	121			124			127			138		
2.4 kv./in.	121			124			126			138		
3.6 kv./in.	121			124			127			141		
4.8 kv./in.	118			122			125			143		
RW$_i$-2												
A	117			123			125			148		
B	120			125			127			138		
C	121			126			127			148		
D	122			127			128			151		
E	118			124			126			151		
	52 days			52 days			52 days			52 days		
LGB$_i$-1												
A	123			128			132			---		
B	126			130			134			---		
C	126			131			133			---		
D	126			132			135			---		

[1] Temperatures for 100 percent mortality are merely the first observed points where 100 percent mortality was obtained. Considerable variation should be expected due to the small slope of the mortality curve in this high mortality region.

Note: LT values appearing in parentheses in the table were taken from the mortality curves drawn between the points for the untreated check insects and the points for treated insects. Therefore, these values may not always correspond accurately with what might have been obtained if intermediate points had been obtained by treatment.

TABLE 20.--Reproduction by adult rice weevils which were injured in high-frequency electrical treatments

Experiment RW$_a$-3, January 3, 1957

Sample temperature, treatment and length of exposure	Temp. after treatment	One week after treatment		Reproduction data			
		Dead	Inj.	Parent insects[1]	Quantity of wheat	Progeny after 6 wks.	Increase of progeny over parents
	°F.	Pct.	Pct.	No.	Grams	No.	Pct.
86° F. at 5 mc. and 3.5 kv./in.:							
6 seconds	91.3	51.7	47.2	42	210	200	476
12 seconds	98.9	89.0	11.0	10	50	23	230
18 seconds	105.7	95.6	4.4	4	25	3	60
24 seconds	114.7	99.0	1.0	1			
86° F. at 10 mc. and 3.5 kv./in.:							
4 seconds	97.1	96.6	3.4	3	20	8	200
8 seconds	106.7	98.9	1.1	1			
86° F. at 10 mc. and 1.2 kv./in.:							
30 seconds	95.5	6.7	5.6	5	45	98	109
60 seconds	103.5	10.0	5.0	4			
90 seconds	110.3	42.7	30.3	27	135	130	481
120 seconds	121.6	58.7	31.5	19	95	180	947
150 seconds	124.0	61.4	28.4	17	90	80	444
180 seconds	131.8	97.7	1.1	1			
86° F. at 39 mc. and 3.5 kv./in.:							
1 second	94.3	92.1	7.9	7	45	46	511
2 seconds	100.5	98.9	1.1	1			
3 seconds	109.2	98.9	1.1	1			
102° F. at 39 mc. and 3.5 kv./in.:							
.75 second	105.2	93.9	6.1	6	35	13	186
1.5 seconds	108.2	98.7	1.3	1			
48° F. at 39 mc. and 3.5 kv./in.:							
5 seconds	100.0	88.9	11.1	1	60	44	367
4.5 seconds	94.6	88.0	12.0	11			
6 seconds	108.2	97.8	2.2	2	15	14	467
7 seconds	113.0	98.9	1.1	1			
Checks...........................				5	25	24	480
				10	50	142	1,420
				15	75	167	1,113
				20	100	196	980
				25	125	280	1,120
				30	150	235	783
				35	175	380	1,086
				40	200	463	1,158
				45	225	456	1,013
				50	250	487	974

---

[1] Injured adults and checks (untreated adults) were placed in culture wheat 11 days after treatment and removed from the wheat 7 days later.

TABLE 21.--Reproduction by adult rice weevils after treatment with high-frequency electric energy at 38.6 mc.

Experiment RW_a-5, March 6, 1957

Field intensity and length of exposure	Temperature after treatment	Living adults after 1 day	Living adults after 1 week	Reproduction data	
				Progeny after 6 weeks	Increase of progeny over parents
	°F.	Number	Number	Number	Percent
4.8 kv./in.:					
.3 second	90.2	94	15	39	41
.8 second	99.0	64	1	0	0
1.3 seconds	103.4	52	0	0	0
1.8 seconds	111.5	13	0	0	0
2.3 seconds	120.4	0	0	0	0
2.8 seconds	128.3	0	0	0	0
6.0 kv./in.:					
.1 second	89.0	99	25	39	39
.4 second	96.3	72	1	3	4
.7 second	103.6	45	0	0	0
1.0 second	111.3	15	0	0	0
1.3 seconds	112.0	14	0	0	0
23.0 kv./in.:					
.1 second	90.0	90	13	34	38
.3 second	96.3	62	0	2	3
7.3 kv./in.:					
.5 second	103.8	42	0	0	0
.7 second	110.0	16	1	0	0
6.0 kv./in.:					
.4 second (2 pulses)	96.6	77	0	0	0
.8 second (4 pulses)	106.8	65	0	0	0
1.2 seconds (6 pulses)	116.8	15	0	0	0
Checks........................	--	99	96	616	622

TABLE 22.--Reproduction by adult confused flour beetles after treatment with high frequency electric energy at 38.6 mc.

Experiment CFB$_a$-1, March 5, 1957

Field intensity and length of exposure	Temperature after treatment	Living adults after 2 days	Living adults after 1 week	Reproduction data	
				Progeny after 6 weeks	Increase of progeny over parents
	°F.	Number	Number	Number	Percent
3.6 kv./in.:					
.5 second	85.0	100	97	220	220
1.0 second	89.9	75	68	240	320
2.0 seconds	97.6	43	28	16	38
3.0 seconds	105.7	16	14	14	88
4.0 seconds	115.9	2	0	0	0
5.0 seconds	123.1	1	0	0	0
4.8 kv./in.:					
.3 second	87.5	96	96	150	156
.8 second	96.9	36	31	35	97
1.3 seconds	100.4	33	30	38	115
1.8 seconds	107.4	28	22	8	29
2.3 seconds	115.5	2	2	0	0
5.9 kv./in.:					
.1 second	86.0	96	93	240	250
.4 second	92.4	66	59	150	227
.7 second	99.9	25	21	1	4
1.0 second	108.2	10	9	0	0
1.3 seconds	108.5	18	14	7	39
6.8 kv./in.:					
.1 second	86.3	80	72	190	238
.4 second	106.7	43	35	65	151
.7 second	106.9	18	9	4	22
Checks........................	--	99	97	115	116

Results of the experiments will be discussed in general, each insect species and stage considered separately. Results may be studied more in detail by referring to graphical and tabular data. Further interesting observations are considered in the discussion section of this report.

Results with Rice Weevil Adults

In experiments RW_a-1, 2, 3, 4, and 5, adult rice weevils were treated in a medium of wheat. Mortality curves are shown in figures 6 through 13. Experiments RW_a-1 and 2 were designed to compare the efficiencies of different field intensities with all other variables held as constant as possible. In addition, wheat of lower moisture content was used in RW_a-2 to determine what influence moisture content might have on the effectiveness of the treatment. The results indicated no discernible difference in insect mortalities due to HF treatments whether wheat moisture content was 12.8 percent or 11.4 percent. In both experiments there was a considerable increase in insect mortality between the first count, 1 day after treatment, and the count at 1 week. In RW_a-1, mortality counts 2 weeks after treatment were essentially the same as those 1 week after treatment; so the 2-week count was eliminated in subsequent experiments with adult rice weevils. The delayed mortality effects were more pronounced with the higher field intensities than with the lower ones. For killing adult insects, a great advantage was found in both experiments in using high field intensities as compared with the lowest field intensity of 1.2 kv./in. (1,200 volts per inch), r.m.s. Differences between treatments at 2.4, 3.6, and 4.8 kv./in. were not as well defined, but the 3.6 and 4.8 kv./in. treatments were definitely more efficient than the lower values 1 week after treatment. Data obtained for 5.3 kv./in. treatments were insufficient for accurate comparison. At the higher field intensities, lethal grain temperatures for 100 percent mortality were about 120° F. at 1 day and about 102° F. at 1 week. Many insects were found to be injured when the first count was made and the majority of these died later.

In experiment RW_a-3 an attempt was made to compare treatments at three different frequencies while holding all other variables constant. Results indicated that treatments at 10- and 40-mc./second were generally more efficient than treatment at 5-mc., especially at the 1-day count. In producing 100 percent mortality at 11 days, however, there appeared to be very little difference in the three frequencies. As figure 12 illustrates, this experiment also revealed a marked difference between higher and lower field intensities, the high field intensities being much more efficient in controlling adult rice weevils. Some preliminary tests were run on grain and insect samples which were preconditioned at different temperatures prior to treatment. The results obtained were verified by the following more complete experiment, RW_a-4.

Experiment RW_a-4 was designed to yield some information concerning the relative heating rates of the adult rice weevil and the wheat during treatment. Sample boxes of wheat and insects were conditioned over night at four different temperatures and maintained at these temperatures until just before treatment. The mortality curves obtained are shown in figure 13, which will be discussed later in greater detail. A comparison of insect mortalities taken from these curves is presented in table 5. The table shows that generally, of samples raised to any particular temperature by treatment, those which started at lower temperatures had higher resulting mortalities. The mortalities obtained indicate that something other than the temperature of the grain must account for the death of the insects at mortalities of 80 percent or less. Differential heating can account for this if the insects are selectively heated at a faster rate than the wheat. It should also be pointed out that check insects conditioned in an oven at 103° F. for 16 hours suffered only 4 percent mortality after 1 day, whereas insects exposed to high-frequency treatment in this experiment suffered 36 to 70 percent mortality when the temperature of the wheat reached 100° F. This observation lends further support to indicate differential heating. A further discussion of the differential heating effects and the results of this experiment follows in the discussion section of this report.

In experiment RW_a-5 very high field intensities and very short exposures were employed. In addition, intermittent application of the field was used at one of the high field intensities for comparison with a sustained treatment at the same field intensity (6.0 kv./in.). There appeared to be very little difference between the sustained treatments at 4.8, 6.0, and 7.3 kv./in., but the intermittent application at 6.0 kv./in. appeared to be less efficient than the sustained treatment with comparable energy application. Grain temperatures of less than 100° F. produced insect mortalities of 100 percent at 1 week after treatment. Some arcing and burned kernels were observed at these high field intensities, but none was observed with the intermittent treatments.

Results with Immature Stages of the Rice Weevil

Two experiments were conducted using immature stages of the rice weevil in wheat. In experiment RW_i-1 the samples represented a composite of all immature stages, while in experiment RW_i-2 the immature stages were separated into different age groups such that the egg, larval, and pupal stages were fairly well divided. The emergence curves shown in figures 17 and 18 reveal three very interesting results. First, treatments producing much higher grain temperatures are required for control of the immature stages than are needed for adults. Secondly, no marked difference in the efficiencies of high and low field intensities was obtained as was so pronounced with the adult insects. Thirdly, little distinguishable difference was found in the susceptibility of the different immature stages to the high-frequency treatment. It was further noted that the treatment apparently slowed down the development of the immature insects. In RW_i-1, 41 percent of the total emergence (6 weeks after treatment) was obtained in the 4-week count for the untreated check insects, whereas only 33 percent of the total emergence was obtained at 4 weeks for the insects in 97° F. treatments. The average for all treated samples shows only 24 percent of the total emergence in the first count at 4 weeks. Retarded development was also noted in RW_i-2 as shown in table 9 where the percent of total emergence at 5 weeks is compared for treated and untreated samples. In the latter experiment it was also noted that injuries occurred with pupae and pre-emergence adults. These injuries were of the same type inflicted when adult rice weevils were treated in wheat. As may be seen from table 19, the LT_{50}, LT_{90}, and LT_{100} (lethal temperature for indicated percent mortality) values for the two experiments are in very close agreement being about 120°, 127°, and 150° F., respectively. An apparent increase in emergence of the two younger stages due to low level treatments which did not elevate the grain temperature more than about 20° (fig. 18) is shown.

Results with Confused Flour Beetle Adults

Results of two experiments with confused flour beetles are given in tables 12 and 13 and are plotted in figures 19, 20, 21, and 22. Experiment CFB_a-1 was conducted with the insects in wheat in order to make comparisons with rice weevil studies where wheat was used. Experiment CFB_a-2 employed wheat shorts as a medium to determine what effect a different medium might have on the efficiency of the treatment. These comparisons between species and media will be treated in the discussion section of the report. As may be seen in figures 19 and 20, there was not a great difference in the mortality at 2 days and at 1 week. Also, there appeared to be little difference in the effectiveness of any of the field intensities used (3.6, 4.8, 5.9, and 6.8 kv./in.).

For the experiments using wheat shorts, two different field intensities were employed, 3.6 and 7.2 kv./in. Little difference between the efficiencies of the two treatments was noted except that after 3 weeks the higher field intensity appeared to produce a definitely higher mortality than the 3.6 kv./in. treatment, i.e., the delayed mortality effect was more pronounced with the 7.2 kv./in. treatment. An examination of table 19 shows considerable difference between the lethal temperatures required for a given mortality in wheat and in wheat shorts. For example, the LT_{90} for the 3.6 kv./in. treatment at 1 week is 108° F. for wheat and 138° for wheat shorts. It is also of interest to note that only a small percentage of the injured confused flour beetles died, whereas most of the injured rice weevils were dead after 1 week. The percentages of injured flour beetles were nearly equal in the 2-day and 1-week counts but decreased in the 3-week counts. The indications were that a few of the injured flour beetles died and several recovered from their injuries and appeared normal.

Results with Confused Flour Beetle Larvae

Experiment CFB_1-1, table 13, using confused flour beetle larvae in wheat shorts with treatment at 3.6 kv./in. produced the mortality curves shown in figure 23. Very little change in mortality between 1 week and 3 weeks was found. Surviving larvae pupated and emerged as normal-appearing adults. No reproduction tests were made. The LT_{90} of 137° F. for the 3.6 kv./in. treatment at 1 week was about the same as was found for the adult confused flour beetle under similar conditions in experiment CFB_a-2.

Results with Red Flour Beetle Adults

Results of experiment RFB_a-1, table 14, using red flour beetle adults in wheat shorts are illustrated in figure 24. Delayed mortality was slight, especially after 1 week. The red flour beetle was found somewhat more susceptible to treatment than the confused flour beetle as indicated by an LT_{90} of 117° F. for the 3.6 kv./in. treatment after 1 week. Many red flour beetle adults were injured by treatment when counted at 1 day and 1 week, but after 3 weeks many of them had recovered and some more had died according to counts taken. Adults which survived the treatment were able to reproduce.

Results with Granary Weevil Adults

Mortality curves obtained from the data of table 15 treating adult granary weevils in wheat are shown in figure 25. A pronounced delayed effect was evidenced by a marked increase in mortality between the 1-day and 1-week counts. Very little change in mortality between 1 week and 2 weeks was found. The delayed effect was similar to that obtained with rice weevils in wheat. An LT_{90} of 100° F. was obtained after 1 week for the 3.3 kv./in. treatment. Many injured insects were counted at 1 day, but a large percentage of them had died at the time of the 1-week count, and a very slight increase in mortality was noted at 2 weeks.

Results with Lesser Grain Borer Adults

An experiment with lesser grain borer adults treated in wheat revealed that they were somewhat more resistant to the treatment than other species tested, table 16. There was a considerable delayed mortality effect. The increase in mortality between 1 week and 2 weeks after treatment appeared to be about the same as the increase between 1 day and 1 week as shown in figure 26. An LT_{90} of 126° F. was obtained for the 3.6 kv./in. treatment after 1 week. No treatment injury data were taken because the insects suffered injury to appendages in vigorous sifting for separation from wheat in preparation of samples.

Results with Immature Stages of the Lesser Grain Borer

Results for experiment LGB_i-1, table 17, in which immature stages of the lesser grain borer in wheat were treated at 3.6 kv./in., are shown in figure 27. Age groups into which the insects were divided for treatment are also listed in table 17. Very little difference was noted in the reaction of different stages to the treatment, with the exception that for the youngest group, emergence appeared to be noticeably increased by the lower range of treatments which produced little mortality in the other stages. The emergence for the egg stage was more than 40 percent higher for one of these treatments than the untreated check. An LT_{90} of about 134° F. was found for the 3.6 kv./in. treatment of the immature stages.

Results with Dermestids

Results for experiment Dm_1-1 are given in tables 18 and 19 and in figures 28 and 29. Two frequencies (38.6 and 10.2 mc.) and two field intensities (3.6 and 1.2 kv./in.) were employed. The combination of 38.6 mc. and 3.6 kv./in. proved to be most effective, with mortalities approaching 100 percent 2 days after treatment for 9 seconds which produced an average wheat temperature of 158.7° F.

Exposure to 38.6 mc. and 1.2 kv./in. resulted in an unusual 2-day mortality response (fig. 28) in that samples in treatments producing temperatures above 140° F. apparently had decreasing mortalities. The maximum temperature reached in this particular series (157.8°) resulted in an apparent average 2-day mortality count of 38 percent; whereas the maximum apparent average 2-day mortality (71.8 percent) was associated with a treatment temperature of only 139°. The delayed mortality effect was pronounced, and eliminated the unexplained 2-day mortality curve by the time of the 2-week counts.

Treatments at 10.8 mc. and 3.6 kv./in. were least effective, as illustrated by the higher LT-values required for any given kill.

REPRODUCTION STUDIES

Results of the limited reproduction experiments showed that both the rice weevil and the confused flour beetle did reproduce after treatment of adults. These data are presented in tables 20, 21, and 22. Examination of table 20 reveals that adult rice weevils which sustained conspicuous physical injuries due to high-frequency treatments were only half as prolific as untreated check insects. Table 21 shows that only rarely did reproduction occur when all adult insects were dead at the second count (1 week after treatment), even though several survivors were present 1 day after treatment. Data in table 22 indicated that the confused flour beetle was able to reproduce at a higher rate after mild treatments than were the untreated controls. More severe treatments greatly inhibited reproduction in these tests.

DISCUSSION

Individual experiments have already been briefly discussed in the results section. Figures 30-35 illustrate some more comparisons to be made. Concepts relative to the application of high-frequency electric fields for stored-grain insect treatment will be further developed.

Injuries and Delayed Effects on Exposed Insects

In figures 30, 31, and 32, two curves are drawn on each chart dividing the total insect population of the samples into three percentages, normal, injured, and dead. Most exposures injured a large percentage of the rice weevil adults which were not killed as determined by mortality and injury counts 1 day following treatment (figs. 30 and 31). Few injured insects remained, however, after 1 week, and the great majority of these, counted as injured at 1 day, died rather than recovered after 1 week. Very little difference was found between the counts at 1 week and 2 weeks. A few more of the injured insects died. In comparing figures 30 and 31, the important influence of field intensity is again noted, the higher field intensity being much more efficient in killing the adults. Injury was also more pronounced with the higher field intensity. With the low field intensity, where all of the insects were not injured at 1 day, a few additional injured insects were counted after 1 week. Figure 32 clearly shows another interesting point. Plotted in

EFFECTS OF 38.6 MC. TREATMENT ON RICE WEEVILS IN WHEAT

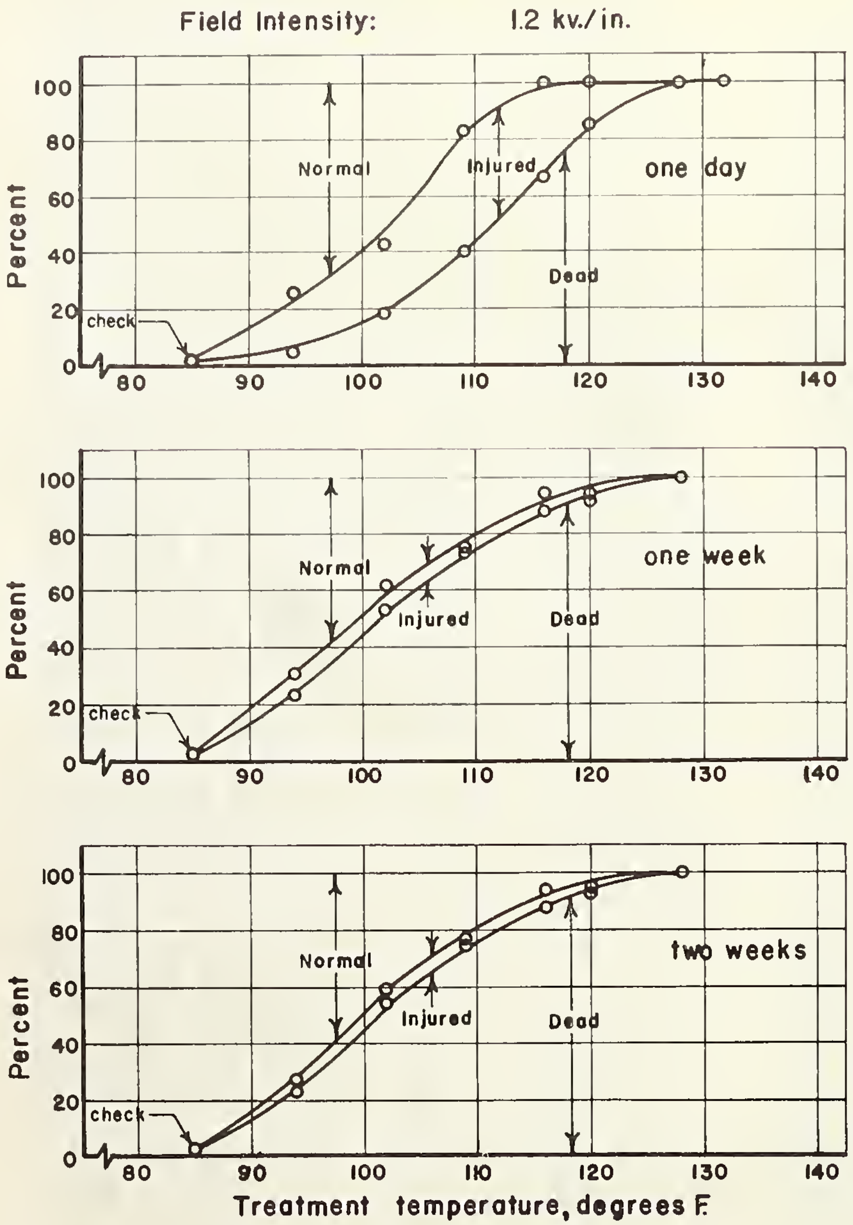


Figure 30. --An example of the delayed effects from high-frequency treatment of adult rice weevils at a low field intensity.

EFFECTS OF 38.6 MC. TREATMENT ON RICE WEEVILS IN WHEAT

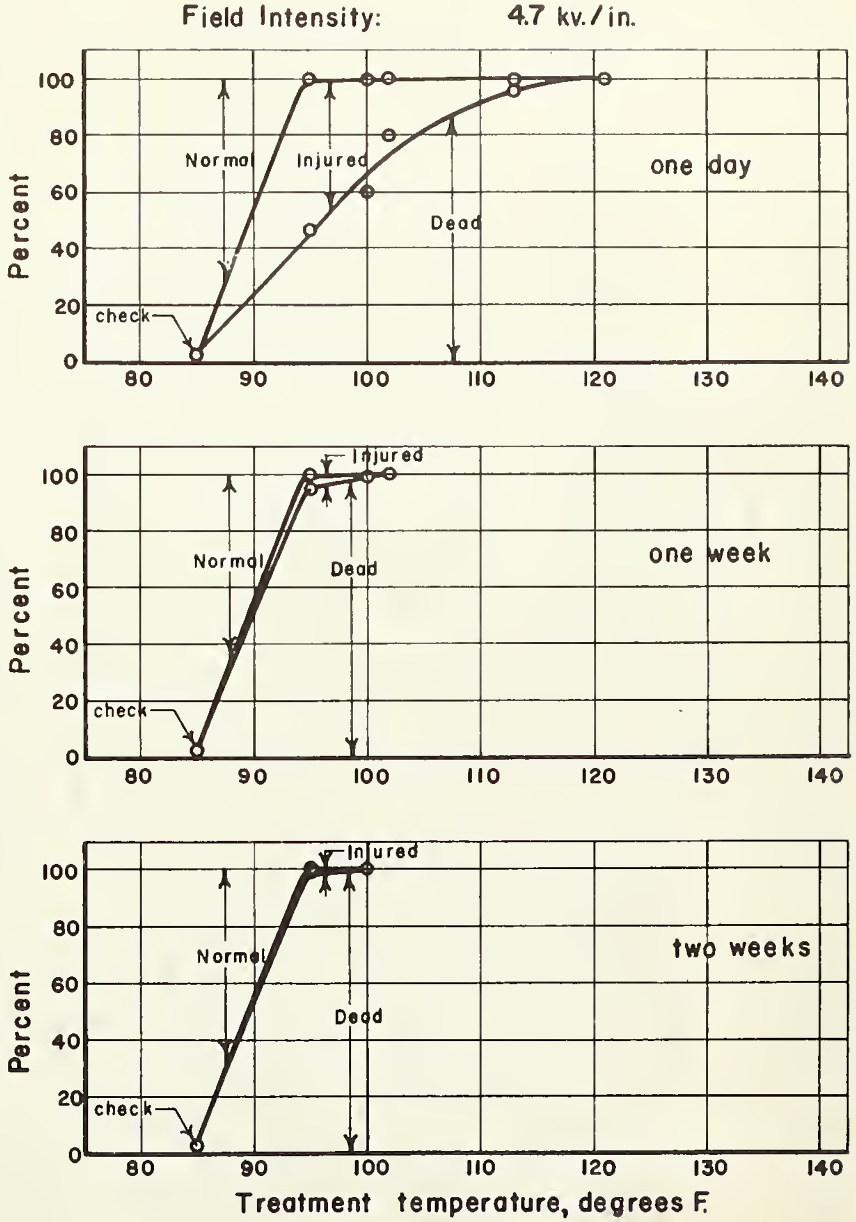
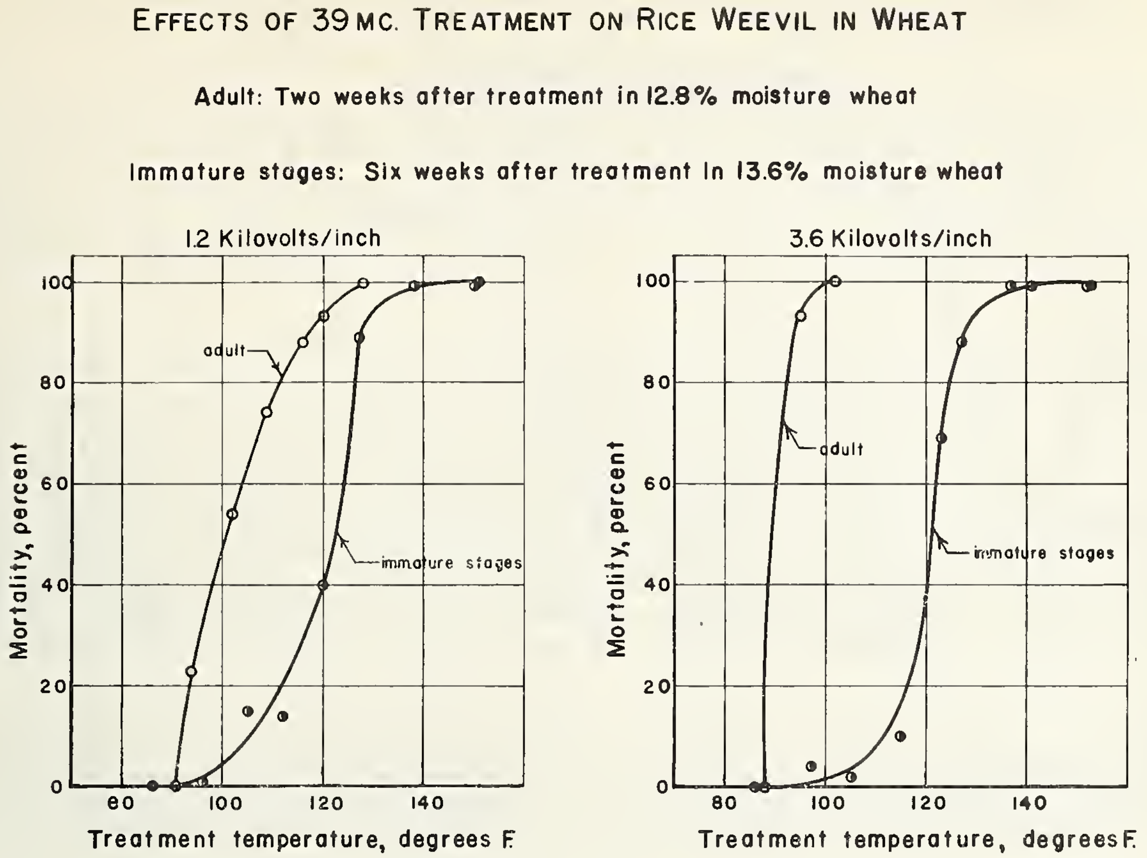


Figure 31. --An example of the delayed effects from high-frequency treatment of adult rice weevils at a high field intensity.



EFFECTS OF 39 MC. TREATMENT ON RICE WEEVIL IN WHEAT

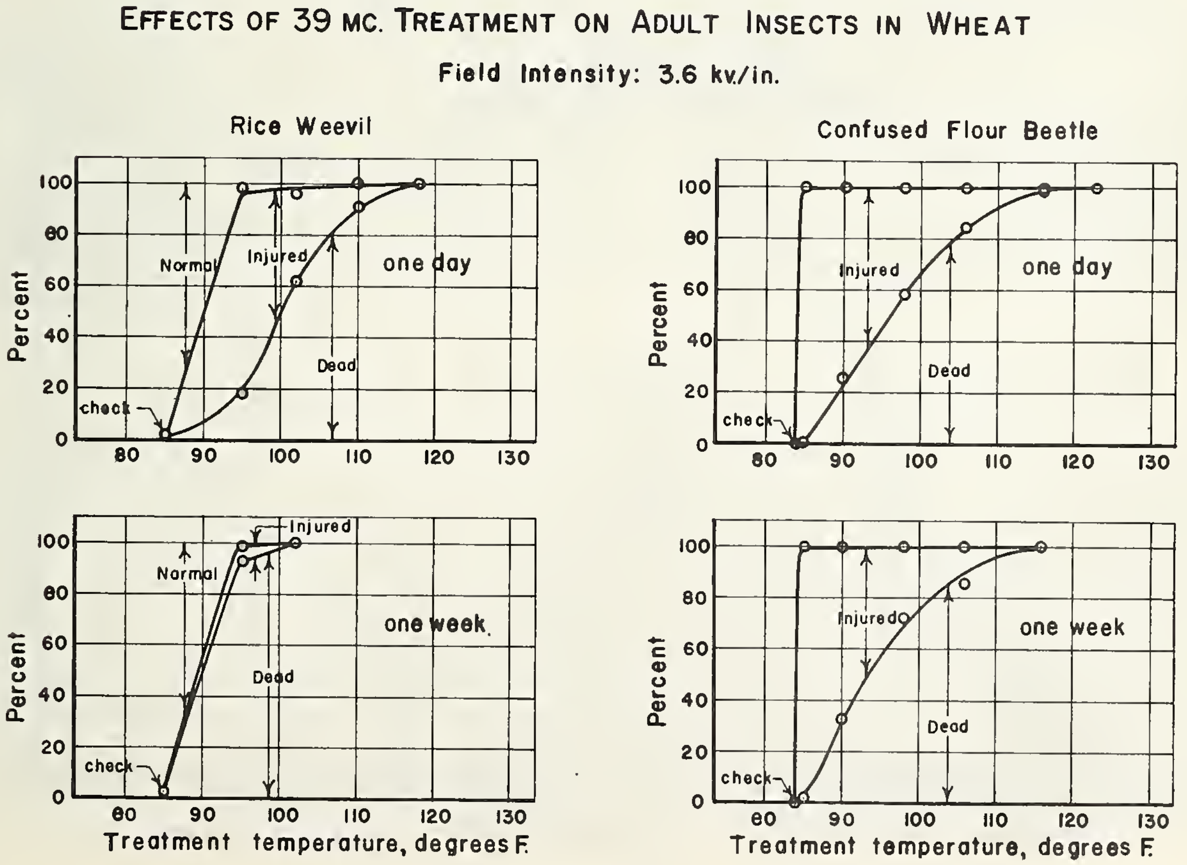
Adult: Two weeks after treatment in 12.8% moisture wheat

Immature stages: Six weeks after treatment in 13.6% moisture wheat

1.2 Kilovolts/inch

3.6 Kilovolts/inch

Figure 33. --Comparison of adult and immature rice weevil mortalities after high-frequency treatment.



EFFECTS OF 39 MC. TREATMENT ON ADULT INSECTS IN WHEAT

Field Intensity: 3.6 kv./in.

Rice Weevil

Confused Flour Beetle

Figure 32. --Comparison of effects of high-frequency treatment on rice weevils and confused flour beetles.

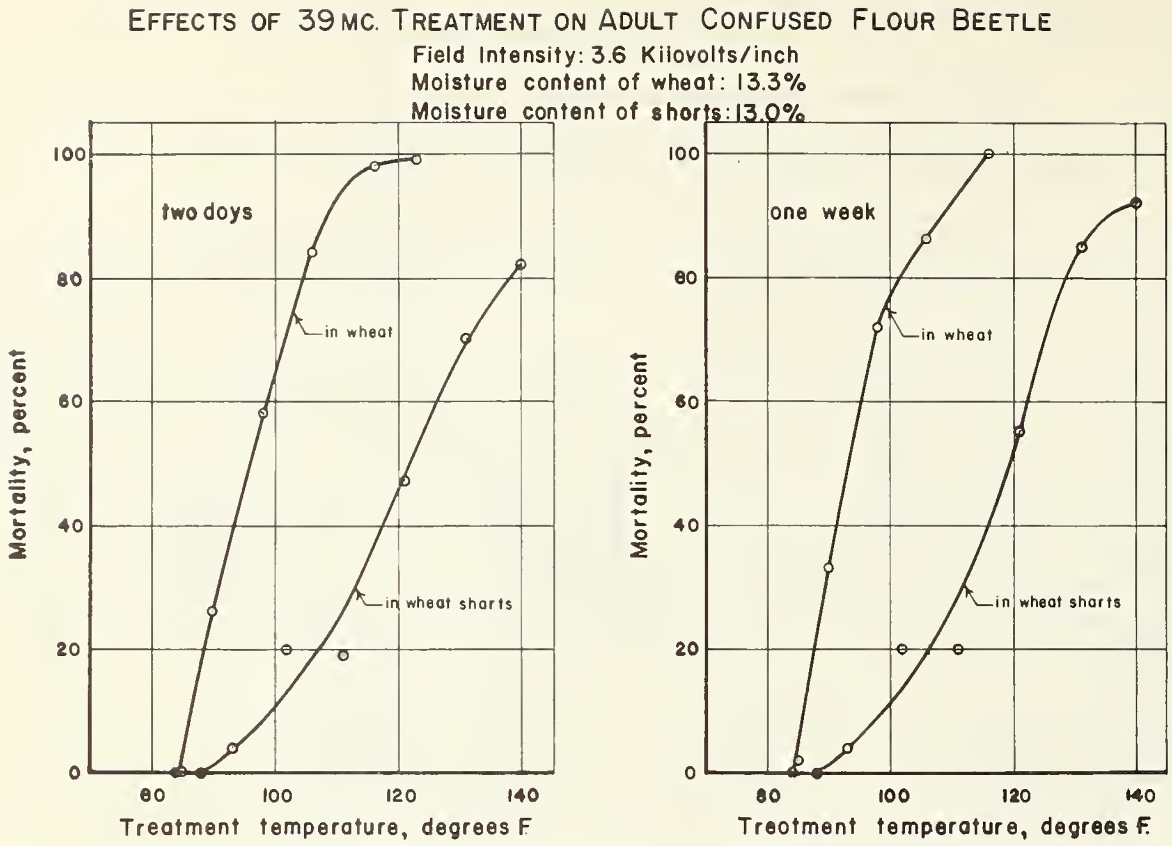


Figure 35. --Comparison of insect mortalities after high-frequency treatment in wheat and in wheat shorts.

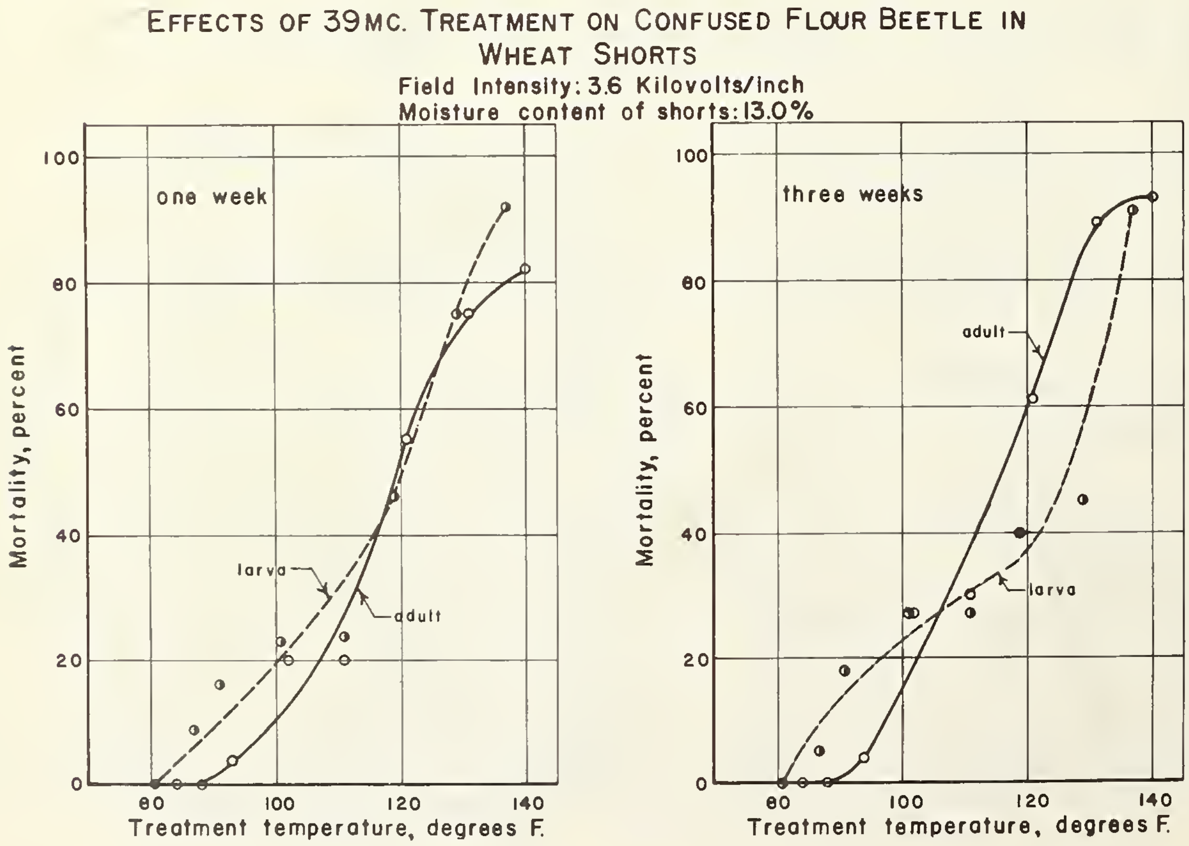


Figure 34. --Comparison of adult and larval confused flour beetle mortalities after high-frequency treatment.

the same way as the previous two figures, it compares identical treatments of adult rice weevils and adult confused flour beetles. All of the confused flour beetles were injured, even by the shortest treatment, but after 1 week very few of the injured confused flour beetles had died and none showed any recovery either. Thus the lethal temperatures determined from the 1-day count were practically the same for the two species, but the lethal temperatures at 1 week were much higher for the flour beetles than for the rice weevils. The injuries to the adult insects appeared in the appendages, especially in the joints of the legs. The legs were doubled over or completely broken off. The insects often moved around on stumps of femora and tibiae.

Comparison of the Effects of Treatment on Adults and Immature Stages

It has already been pointed out that the immature stages of the rice weevil are more difficult to kill with the high-frequency treatment than the adults, and that the field intensity had very little effect on the efficiency of the treatment as far as the immature stages are concerned. These points are emphasized in figure 33 where the emergence information from experiments with immature stages has been transformed into percentage mortality and plotted on the same chart with adult mortality information. These curves show a difference in the LT_{90} for adults and immature stages of only 10° F. when treated at 1.2 kv./in., whereas the difference in the LT_{90} for the two stages treated at 3.6 kv./in. is 34°.

To compare the effects on the adult and larval stages of the confused flour beetle, the information obtained when the two stages were treated separately in wheat shorts has been plotted on the same graph in figure 34. One week after treatment there appeared to be no appreciable difference between the susceptibility of the adults and larvae. At 3 weeks the larvae appeared to be slightly more resistant in the range from 50 to 80 percent mortality. The delayed effect was not very pronounced for either stage, but a few additional adults died between the 1- and 3-week counts, whereas some larvae appeared to recover.

Comparison of Wheat and Wheat Shorts as Treatment Media

A comparison of treatment in wheat and in wheat shorts is presented for confused flour beetle adults in figure 35. Much higher temperatures were required in wheat shorts than in wheat for comparable mortality. This can be explained by a lower expected differential heating factor for the insects in shorts than for the insects in wheat. This factor will be discussed in further detail later, and reference to the comparison between treatment in wheat and wheat shorts will be made at that time. For the present, it is sufficient to note that for treatment of the adult confused flour beetle in wheat, LT_{80} values of 104° F. at 2 days and 102° at 1 week were obtained, whereas for wheat shorts the corresponding values were 137° and 127°.

Differential Heating of the Insects and the Treatment Media

The possibility of selectively heating the insects when treating infested grain with high-frequency electric fields is not only of technical interest, but also of practical significance. If the insects could be heated at a faster rate than the wheat through dielectric heating, the high-frequency method would offer that advantage over conventional methods of heating, which are generally too costly for economical use solely for insect control, in addition to the advantages of a high-speed treatment. The theoretical equation for the heating rate of a homogeneous material when subjected to a high-frequency field has already been presented in the introduction section of this report. (See Equation 1.) In examining this equation, it is seen that the values of K and F will be the same for both the insects and grain. All other factors determining the heating rate may be different for the insects and the grain. The dielectric loss factor, ε'', has been determined for the wheat and wheat shorts used in every experiment by the method of measurements already mentioned. Measurements of the dielectric properties of a large mass of adult rice weevils and also of adult confused flour beetles have been made using the same method. Values for the density and specific heat of wheat are available in the literature,[8] and reasonably good estimates can be made for the density and specific heat of the insects. The value of E for the grain can be calculated by using Equation 2, when the other treatment variables are known. The value for E for the insects is more difficult to obtain. It may be estimated with caution by considering the insect as a sphere embedded in an infinite medium of wheat. From electrical theory, the relationship between the field in a sphere embedded in an infinite medium and the field in the medium is given by:

$$E_1 = E_2 \left(1 - \frac{\varepsilon_1 - \varepsilon_2}{2\varepsilon_2 + \varepsilon_1}\right), \qquad \text{(Equation 4)}$$

where E_1 represents the field intensity in the sphere, E_2 the field intensity in the medium, ε_1 the complex permittivity of the sphere and ε_2 the complex permittivity of the medium. The complex permittivity, ε, is related to the real permittivity or the dielectric constant, ε', and the dielectric loss factor, ε'', by the following relation:

$$\varepsilon = \varepsilon' - j\varepsilon'', \qquad \text{(Equation 5)}$$

where $j = \sqrt{-1}$, and the magnitude of ε may be calculated as $\sqrt{(\varepsilon')^2 + (\varepsilon'')^2}$ or $\dfrac{\varepsilon''}{\sin\left(\tan^{-1} \frac{\varepsilon''}{\varepsilon'}\right)}$.

Unless the moisture content of the grain is very high, the dielectric loss factor is negligible in comparison to the real permittivity, and the real and complex permittivity have the same value. For this reason, no distinction between the two is necessary, and none has been made elsewhere in this report. In the case of the insects, however, the loss factor is significantly large, and it should be taken into account in calculating the complex permittivities of the insects. The average value for the complex permittivity obtained from three separate measurements on masses of adult rice weevils was 6.6 at room temperature and 40 mc./sec. The permittivity of the wheat used in experiment RW_a-4, which will soon be discussed, was 4.2 under the same conditions. Using these values in Equation 4, it is seen that the intensity of the field applied to the adult rice weevils in wheat is about 0.84 times that in the wheat based on the above reasoning.[9] The values obtained by measurement for the dielectric loss factor of a mass of rice weevils and of the wheat used in experiment RW_a-4 were 2.2 and 0.5, respectively. The bulk density of the wheat and that of the rice weevil can be expected to be of approximately the same value. The specific heat of the wheat was taken as 0.4 and that of the insects estimated as 0.7. Using these figures in connection with Equation 1, the expected ratio of the heating rate of the rice weevils to the heating rate of the wheat would be 1.8. The ratio of the two heating rates has been designated the differential heating factor, f.

Experiment RW_a-4 was performed to obtain an experimental value for the differential heating factor. Results of this experiment were merely mentioned in the results section. The analysis of the results of this experiment will now be taken up in detail. Conditions for the experiment and results of the experiment and the analysis are summarized in figure 13. The wheat and the adult rice weevils were conditioned in the plastic boxes overnight at four different temperatures prior to treatment (47°, 60°, 86°, and 103° F.). The samples were maintained at these temperatures until just before treatment, so the initial sample temperatures were very near the preconditioning values. Several exposures were given to each group, and from mortality counts made 1 day after treatment, a mortality curve was plotted for each group. These are the curves shown in figure 13.

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[8] Engineering data on grain storage, Agricultural Engineering Data 1, A. E. Index 11.732, Published by the American Society of Agricultural Engineers, St. Joseph, Mich., May 1948.

[9] Since the measurements of permittivity and loss factor were made on insects in bulk, the values obtained apply in effect to the insect and its share of the surrounding space. "Field intensity in the insect" refers to a sort of average for the insect and its associated space envelope.

The analysis is based on the assumption, which may be subject to some question, that there is a critical temperature, T_c, which results in a certain mortality if the insects themselves are raised to this temperature momentarily.

Then if the ratio of the average heating rate of the insects to the average heating rate of the grain is designated as the differential heating factor, f, the following equation may be written:

$$T_c = T_{ig} + f \, \Delta T_g \qquad \text{(Equation 6)}$$

where T_{ig} represents the initial temperature of the grain and insects, and ΔT_g the elevation of the grain temperature produced by the treatment. Since T_{ig} is known and ΔT_g can be determined from the curves for any particular mortality, two unknowns remain in Equation 5, T_c and f. For any particular mortality an equation may be written for each curve and a system of simultaneous equations set up. Since there are only two unknown quantities, T_c and f, only two equations and thus only two curves are required; however, additional curves provide more equations and more solutions for comparison. The solutions to the six pairs of simultaneous equations for a mortality of 50 percent are shown on figure 13. The mean value for f is 1.52 which appears to be in good agreement with the theoretically predicted value of 1.8. Further examination of figure 13, however, raises the question of the reason for the apparent convergence of the curves if the differential heating factor really is this large. To answer this question, the differential heating factor was calculated for 20, 40, 60, and 80 percent mortality, also, and solutions compared.

The following are the mean values obtained for the differential heating factor, f, and the critical temperature, T_c.

Percent Mortality	f	T_c
20	2.27	112.8° F.
40	1.71	113.2
50	1.52	113.4
60	1.46	116.0
80	1.24	116.7

From this analysis, it appears that the differential heating factor is not constant, but decreases as the temperatures increase and becomes less important as the mortality approaches 100 percent. Very little difference in the calculated critical temperature was obtained for different mortalities. The analysis was based on an assumption that the T_c value was the same for all four groups. This may not be entirely correct since the different insect groups were pre-conditioned at widely different temperatures. It should be remembered that an analysis so simple as this should not be expected to yield especially accurate and reliable values. It is believed, however, that valid indications are given by the above analysis. It is interesting to note also that the value of f, arrived at on a purely theoretical basis, lies in the range of experimental values obtained. Also, since the values for dielectric properties of insects and grain used in the theoretical calculation were those measured at room temperature, the theoretical value should be expected to be nearer the experimental values obtained for lower temperature treatments. It is encouraging to find that this is true in that the theoretical value lies between the experimental values found for 20 and 40 percent mortality which correspond to the lower temperature treatments.

It has already been mentioned that a difference in the differential heating factors for insects in wheat and for insects in wheat shorts can account for the much higher lethal temperatures found necessary in the culture medium to produce a given mortality when insects are treated in wheat shorts than when they are treated in wheat. A theoretical estimate of the differential heating factor, f, will now be made for confused flour beetles in the two different media. From values of dielectric properties determined for a mass of adult confused flour beetles and similar measurements on the wheat shorts used in experiment CFB_a-2 and the wheat used in experiment CFB_a-1, these estimates may be worked out using Equations 1 and 3 in the same way that a value of f for rice weevils in wheat was estimated previously. The values obtained for the complex permittivity of wheat, wheat shorts, and confused flour beetles were 4.26, 2.79, and 7.84, respectively. Using Equation 3, it is found that the field intensity in the insects may be expected to be 0.77 of that in the medium for wheat and 0.61 of that in the medium for wheat shorts. The values obtained for the dielectric loss factor of the wheat, wheat shorts, and confused flour beetles were 0.51, 0.38, and 2.20, respectively. The density of wheat shorts found by weighing a known volume under the same compaction conditions as it was used in the treatments was 0.53. The specific heat of the wheat shorts is estimated at 0.4 since the values for wheat and wheat flour are both about 0.4. Using 0.7 for the specific heat of the confused flour beetles as was done for the rice weevils and estimating the density of the insect at 0.7, the expected differential heating factors may be calculated using Equation 1. For the adult confused flour beetles in wheat the value of f obtained is 1.6. For the same insects in wheat shorts the value of f is found to be 0.92. While these values are based on estimates and a simple mathematical model, the large difference obtained in expected differential heating factors for the insects in the two media is believed to explain the experimental results quite satisfactorily. A higher temperature in the medium should be expected to be required when the insects are treated in wheat shorts than when treated in wheat to produce the same mortality.

COSTS OF TREATMENT

No special study of costs of high-frequency electrical treatment to control insect infestations in grain has been undertaken, but an estimate of some general costs can be predicted rather easily. On the basis of the laboratory experiments completed thus far, the grain would have to be given a treatment which would raise the grain temperature to about 150° F. in order to achieve 100 percent kill of all of the immature stages of the insects so far tested. If grain were to be treated in large quantities, it might be found that a lower grain temperature would suffice, since the temperature would be held for a longer period of time than in the laboratory samples which cool rapidly after treatment. For this estimate, however, the figure of 150° F. will be used. If the grain could be treated when the temperature is 80°, then the amount of energy required to raise the temperature of a bushel of wheat 70° would be 0.49 kilowatt-hour using a value of 0.4 for the specific heat and 60 lb./bushel for the test weight. Assuming an efficiency of 50 percent for the conversion of electric energy to heat energy in the grain by the high-frequency equipment, the total energy requirement would be about 1 kw.-hr. per bushel. This efficiency might well be increased by proper design to utilize heat dissipated from the plate of the oscillator tubes to preheat the grain coming into the equipment for treatment.

About the largest industrial dielectric heating units now available are 200-kilowatt generators which sell for about $100,000 including equipment for applying the energy to the product. Since this is an output rating, one unit of this size should be capable of treating wheat at a rate of about 400 bushels per hour. Considering the useful life of such a unit to be 10 years, neglecting any salvage value at the end of that time and using straight-line depreciation, considering 2,000 hours' operation per year which amounts to about 12 weeks' continuous operation, taking 2 cents per kw.-hr. as the power cost, and using a manufacturer's recommendation[10] of 60 cents per hour for vacuum-tube and vacuum-condenser replacement and a labor requirement of three man-hours per week for maintenance, the following costs are obtained on a per-bushel basis:

Depreciation	$0.0125 per bushel
Interest on investment	.0025
Power	.02
Tube and condenser replacement	.0015
Maintenance labor	.0002
	$0.0367

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[10] Recommendation given in correspondence from Girdler Process Equipment Division, National Cylinder Gas Co., Louisville, Ky., April 7, 1958.

It is reasonable to expect that such an installation at an elevator could be used to treat the grain when it is being received or otherwise being moved normally so that costs of handling the grain need not be considered. Such an installation if properly designed should be entirely automatic and would not require any skilled operators if the technical maintenance considered above is available on call.

The above figure of less than 4 cents per bushel is higher than an estimate obtained from cost curves supplied by the Westinghouse Electric Corporation using the same conditions.[11] Information from this source for a 200-kilowatt generator including power cost, amortization cost, and vacuum-tube costs, using 2 cents per kw. hr. and amortized on a 30,000-hour operating basis gives a figure of 2.8 cents per bushel. This second estimate includes all of the major costs and is probably based on a more realistic amortization than the first estimate above; however, costs of equipment have probably increased somewhat since the curves were published.

As the most important cost is that of power, estimates for any particular application must take into account the power rates available in the locality. If it were possible to modify the method of treatment in such a way that the insects could be controlled with less energy input to the grain, i. e., without raising the temperature of the grain so high, the capacity of the treating equipment would be increased and the per-bushel cost for depreciation lowered accordingly. The per-bushel power cost would then be less, also. These two costs constitute the major part of the total cost. The question of whether or not this modification can be accomplished is, therefore, important in determining the possibilities for practical application. Further study is also needed to evaluate the benefits of seed treatment to stimulate germination and any beneficial effects of treatment on milling and baking qualities of flour milled from treated wheat. If findings of economical significance in these areas should be turned up, the equipment might well be used for this work as well as insect control and the cost estimates more favorably revised. The possible application of the method for insect control in products other than grain, where time may be a more important factor, should also be kept in mind.

FINDINGS

These studies have reaffirmed earlier conclusions that all stages of some stored-grain insects in wheat can be killed by high-frequency electrical treatments of a few seconds' duration. The treatments do not damage the grain. There are differences in the resistance to treatment among different species and between stages within species. The findings concerning these differences and the effects of different values of treatment variables are as follows:

1. Treatment at a field intensity of 3.6 kv./in., r.m.s., in the grain appears to be considerably more efficient in killing adult insects than treatment at lower field intensities of 2.4 or 1.2 kv./in. For the immature stages of the rice weevil, however, no distinguishable difference was found between treatments at different field intensities below 4.8 kv./in. The maximum field intensity that can be used is limited by arcing in the grain which burns the kernels. With clean grain, little arcing was observed at 4.8 kv./in., but at higher field intensities considerable arcing can be expected. Treatment at 3.6 kv./in. was selected for many of the experiments for treatment free of arcing problems.

2. Experimental evidence of differential heating rates for the insects and the grain, when treated together, has been found which correlates well with theoretical predictions. At room temperature the adult insects are believed to be selectively heated at about twice the rate of the wheat, but as the temperatures rise the differential heating effect is believed to diminish under the conditions employed in these experiments. This effect can also explain different results obtained with the

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[11] Westinghouse Electric Corporation. Here's New Help For You in Radio-Frequency Heating. B-3948, Filing No. 85-100, Industrial Electronics Division, Baltimore, Md., Oct. 1947.

same type of insects treated in different media. It also could account for the fact that a 100 percent kill of adult rice weevils has been achieved by a treatment which did not raise the grain temperature higher than 103° F., whereas insects in wheat from the same culture have survived air temperatures of 103° for 16 hours in an oven with less than 9 percent mortality (fig. 14).

3. Higher level treatments are required for control of adult insects in wheat shorts than are needed for the insects in wheat. Treatments producing temperatures of 102° F. in the wheat were required to produce 80 percent mortality 1 week after treatment, whereas temperatures in the shorts were 127° for the same mortality.

4. No distinguishable difference in the effectiveness of high-frequency treatment was observed when rice weevils were treated in wheat of 11.4 percent moisture and when they were treated in wheat with a moisture content of 12.8 percent.

5. For the insects treated in wheat under the same treatment conditions of frequency (39 mc.) and field intensity (3.6 kv./in.), the following order was established in increasing resistance to the high-frequency treatment: rice weevil adults, granary weevil adults, confused flour beetle adults, lesser grain borer adults, dermestid larvae, immature rice weevils, and immature lesser grain borers. The lethal grain temperatures produced by treatment for 50 percent eventual mortality were respectively 88, 88, 93, 97, 106, 120, and 125° F. The corresponding temperatures for 90 percent mortality were 94, 98, 108, 122, 130, 127, and 134°. For insects treated in wheat shorts, the order in increasing resistance was red flour beetle adults, confused flour beetle adults, and confused flour beetle larvae. Corresponding LT_{50} values were 104, 116, and 120° and LT_{90} values were 116, 132, and 137°, respectively.

6. In the experiments with adult insects nearly all not killed by the various exposures were injured when high field intensities were used. In samples treated with low field intensities and short exposures several normal-appearing insects were observed along with the dead or injured ones. Injuries appeared in the appendages, especially in the joints of the legs. These were doubled over or the appendage completely broken off. The insects often moved around on stumps of femora and tibiae. After 1 week most of the injured rice weevils had died. A few more of the injured granary weevils survived at 1 and 2 weeks than did the rice weevils. Very few of the confused flour beetles and red flour beetles which were injured by treatment died. They did not show any recovery from the injuries at 1 week, but after 3 weeks some recovery of the injured insects and some increased mortality was indicated by mortality and injury counts. With the immature stages of the rice weevil, the same type of injury was shown by emerging adults which were treated in the late pupal or pre-emergence adult stages. Retarded development was noted with other treated immature stages of the rice weevil. Increased total emergence was observed with the youngest stages of both rice weevil and lesser grain borers which appeared to be attributable to treatments of low levels which did not produce much mortality in other stages treated.

7. Limited studies showed that adults of both the rice weevils and the confused flour beetles which survived the high-frequency treatments did reproduce.

8. A simple analysis of costs which might be expected for large-scale treatment of grain with high-frequency generators reveals that electric power costs and depreciation on equipment are the two major costs to be considered. An estimate of 2.8 to 3.7 cents per bushel was arrived at for costs including depreciation, interest on investment, power cost at 2 cents per kw.-hr., vacuum-tube and vacuum-condenser replacement, and labor for maintenance.

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